SWITCHBOARD INSTRUMENTS

NEWNES' "ELECTRICAL ENGINEER" SERIES

General Editor: E. MOLLOY, *Editor of "Electrical Engineer."*

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SWITCHBOARD INSTRUMENTS

A Practical Work for Installation Engineers, Contractors, Plant Engineers and Works Electricians

BY

"PROTON"

GENERAL EDITOR

E. MOLLOY

Editor of "Electrical Engineer"

WITH 135 DIAGRAMS AND PHOTOGRAPHS

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PREFACE

THE progress which has been made in various branches of electrical engineering during the past fifty years is phenomenal. It is doubtful that any equivalent progress has been made in any other branch of applied science.

The reason why progress has been so rapid is because at a very early stage in electrical development accurate measuring instruments were devised by which it was possible to tell exactly what was happening in electrical circuits in any combination of circumstances. Accurate measurement in any science is the first step towards rapid progress. The science of measuring electrical quantities has been developed to an extraordinary degree of accuracy.

Instruments are readily obtainable which will give the visual indication to within one millionth of a volt, or one millionth of an ampere. These, of course, are laboratory instruments and therefore do not form the subject of the present work, which, as its title indicates, deals with the commercial instruments likely to be met with by an electrical engineer in a power station or in an electrically-driven works or factory.

The high degree of accuracy in the electrical laboratory is, however, reflected in the extremely high standards of performance which are expected of modern switchboard instruments.

The first chapter deals with voltmeters and ammeters, which are obviously of the widest interest. Both moving coil and moving iron types are dealt with, and some space has also been devoted to the thermal or hot wire type. Although the latter type is to-day chiefly used in laboratory work, it still has certain industrial applications, particularly in the field of radio research and development.

Another type of instrument which, though largely favoured for laboratory use, has important commercial applications, is the dynamometer type, which, being capable of great accuracy, is largely used for sub-standard instruments in the meter testing department of electricity supply undertakings.

The rectifier type ammeter and the electrostatic voltmeter are also described in this chapter.

The second chapter deals with the measurement of power in electrical circuits. The watt meter is an instrument which shows at a glance the actual electrical horse-power which is

being consumed in the circuit to which it is connected. It will be appreciated that such instruments are of primary importance on the switchboard of a generating station, and to a lesser extent on the factory switchboard, where the plant engineer may be responsible for keeping the maximum demand below a certain specified figure.

Electricity meters form the subject of Chapter III. All the commercial types are dealt with. In addition, the special instruments used for recording maximum demand and reactive kVA are also dealt with.

Closely allied to the question of maximum demand is that of power factor. Instruments designed to measure power factor and frequency form the subject of Chapter IV.

Up-to-date methods of synchronising alternators for parallel running together with a description of the instruments available for this purpose form the subject of a special chapter.

The concluding section deals respectively with instrument transformers and protective relays. In each case notes are given on installation, connexion and maintenance.

We have pleasure in recording our indebtedness to the firms who have so generously assisted us in the compilation of this work by supplying details of their latest types of instruments.

In particular, we would thank:

ELECTRICAL APPARATUS CO., LTD.
GENERAL ELECTRIC CO., LTD.
MEASUREMENT, LTD.
FERRANTI, LTD.
METROPOLITAN-VICKERS ELECTRICAL CO., LTD.
CHAMBERLAIN & HOOKHAM, LTD.
LANDIS & GYR, LTD.
ARON ELECTRICITY METER, LTD.
REASON MANUFACTURING CO., LTD.
EVERETT, EDGCUMBE & CO., LTD.

It is largely owing to the wholehearted co-operation of the above that we are able to present this up-to-date survey of British practice, as applied to electrical switchboard instruments.

It is hoped that switchboard attendants, plant engineers, meter testing engineers, and others who have occasion to use any types of commercial measuring instruments will find this work an unfailing source of assistance in the solution of any practical problems which they may encounter.

PROTON
E. M.

CONTENTS

CHAPTER I

THE MEASUREMENT OF VOLTAGE AND CURRENT

FUNDAMENTALLY all measuring instruments consist of a moving element which is generally suspended on jewelled bearings in order to reduce friction to a minimum. This moving portion which carries the pointer in the case of indicating instruments or the pen in the case of graphic instruments is subject to two separate torques, a driving torque which is a function of the quantity to be measured and a retarding or braking torque which is generally provided by gravity or by means of a control spring.

These two torques are equal when the instrument is in a state of equilibrium. At the same time, some form of damping is generally fitted to the moving part so that it comes to rest quickly after a change has occurred in the quantity to be measured. This may take the form of either pneumatic or electro-magnetic damping.

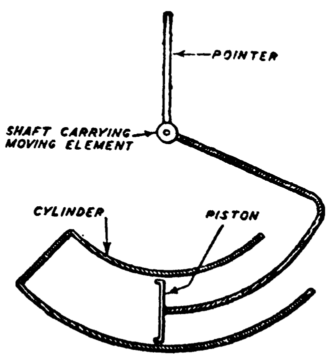


FIG. 1.—PNEUMATIC DAMPING.

Pneumatic Damping.

In the case of pneu-

matic damping a piston, coupled to the moving part of the meter, is allowed to move in a cylinder, hence any movement of the piston is restrained by the enclosed column of air (Fig. 1).

Electro-magnetic Damping.

Electro-magnetic damping in its simplest form consists of a disc of conducting material which is allowed to rotate or oscillate in the air gap of a permanent magnet. The movement of this disc is restrained by the presence of eddy currents in the disc which are generated when the disc cuts the magnetic flux of the permanent magnet (Fig. 2).

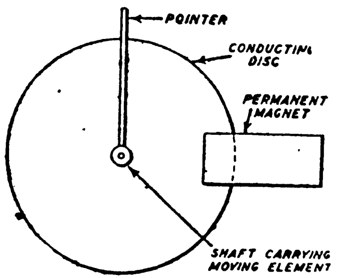


FIG. 2.—ELECTRO-MAGNETIC DAMPING.

The Choice of an Instrument.

The choice of an instrument is dependent upon two factors, the quantity which is to be measured and the accuracy which is required. This latter consideration does not always receive the attention which it merits, so that special emphasis on this point is justified. Where the measurement is used as a basis for making a charge and the values under consideration are large, great care should be taken with regard to accuracy. The finest equipment should always be used for such a purpose, bearing in mind that whilst the initial cost may be greater than a less accurate equipment, it is actually small when compared with the values of the

quantities being measured. On the other hand, where the measurement is required simply as an indication of the circuit conditions, accuracy is not of paramount importance so that it may be sacrificed to some extent in favour of initial cost and general robustness of the design.

The Decision Regarding the Mounting.

Having established the type of instrument required for a particular measurement there remains the decision regarding the class of mounting. This is largely governed by the location, the individual taste of the engineer, and the general layout of the existing plant.

FIG. 3.—ROUND PROJECTING TYPE SWITCHBOARD MOUNTING INSTRUMENT.
(*Electrical Apparatus Co., Ltd.*)

Five Types of Cases.

Generally speaking there are six types of cases in commercial use:—Projecting type, flush mounting type, sector pattern, pedestal type, edgewise pattern and portable pattern, all of which are obtainable with different scalings. Of these the first four are generally used for switchboard mounting, the sector pattern being particularly useful where illuminated dials are required. The last-named type, that is, the portable pattern, is generally used for routine test purposes and general laboratory work.

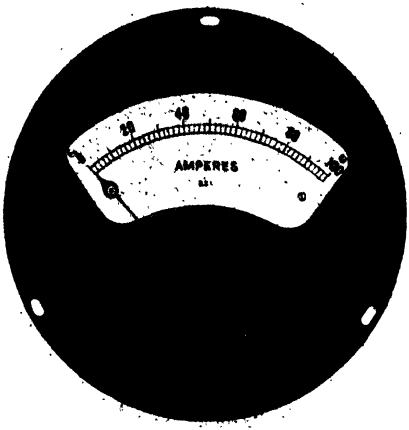


FIG. 4.—FLUSH TYPE INSTRUMENT.
(*General Electric Co., Ltd*)

Ammeters and Voltmeters Compared.

The apparatus for the measurement of volts and amperes is fundamentally the same, and only differs in the fact that the voltmeter is fitted with a coil having a large number of turns, whereas the ammeter is fitted with a coil having a comparatively small number of turns. The reason for this difference becomes apparent when the method of connecting these two instruments into a circuit is known. The voltmeter must be connected across the mains, and hence has to withstand the full pressure of the circuit.

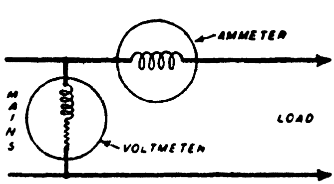


FIG. 5.—THE CONNECTIONS FOR VOLTMETERS AND AMMETERS.

Thus it is obvious that the instrument must possess a high resistance value if the flow of current is to be limited to the requisite milliamperes generally required to operate a voltmeter. On the other hand, an ammeter is connected in series with the load, and must possess a small resistance value, if the losses are to be kept low.

Types of Instruments Used.

The list given below shows the most important types of instruments now available, together with the circuits for which they are suitable.

TABLE I.—TYPES OF INSTRUMENTS USED FOR VOLTAGE AND CURRENT MEASUREMENT.

Measurement.	*D.C. Circuits.*	*A.C. Circuits.*
Voltage .	Moving coil type, thermal type, moving iron type, dynamometer type, electrostatic type.	Thermal type, moving iron type, dynamometer type, induction type, rectifier type, electrostatic type.
Current . .	Moving coil type, thermal type, moving iron type, dynamometer type.	Thermal type, moving iron type, dynamometer type, induction type, rectifier type.

Moving Coil Type of Instrument.

This type is sometimes known as the D'Arsonval type, named after the originator, and is illustrated schematically in Fig. 6. It consists of a coil of wire (*a*) mounted on a copper or aluminium former (*b*), suspended by steel pivots between jewelled bearings (*c*).

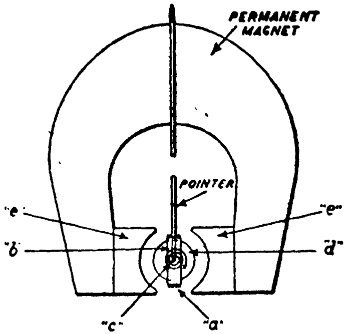


FIG. 6.—DIAGRAM SHOWING ESSENTIAL CONSTRUCTION OF MOVING COIL AMMETER OR VOLTMETER.

a, coil of wire; *b*, former; *c*, jewelled bearings; *d*, soft iron core; *e*, permanent magnet.

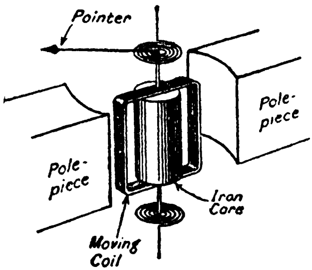


FIG. 7.—DETAILS OF MOVING COIL INSTRUMENT.

Note the two control springs which supply the control torque and the paths for the current into and out of the moving coil.

The whole movement is mounted in the annular space between a soft iron core (*d*) and the pole-pieces attached to a permanent magnet (*e*). The current is led into and out of the coil by the two spiral springs, which also serve to provide the necessary control torque. The pointer is mounted rigidly on the moving coil itself.

The driving torque is produced by the interaction of the fluxes due to the permanent magnet and the current circulating round the moving coil.

The control torque is provided by the two control springs which are made of a material which is practically independent of temperature variation.

The damping is electro-magnetic and is provided by the generation of eddy currents in the metallic former of the moving coil.

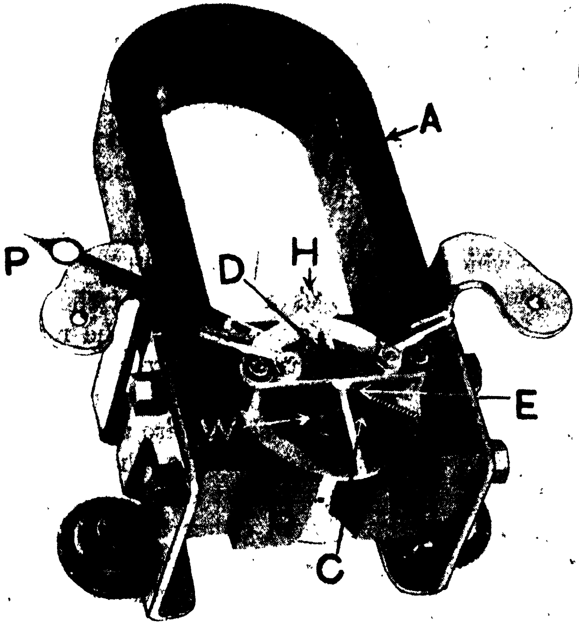


FIG. 8.—TYPICAL MOVING COIL INSTRUMENT WITH SCALE AND COVER REMOVED.

The horseshoe permanent magnet A produces a strong magnetic field in the narrow gap between the pole pieces BB and the cylindrical core C, all of which are of soft iron. In this gap swings the rectangular coil W, which carries the current to be measured, and which is urged to turn round the pivot D with a force proportional to the strength of the current. This twisting force is opposed by that of the spiral spring E, so that the deflection of the pointer P over the scale depends upon the current flowing through the coil W.

(*Everett, Edgcumbe & Co., Ltd.*)

The Characteristics of the Moving Coil Type of Instrument.

Such an instrument is only capable of measuring direct current and provides a linear scale which is a big advantage from the point of view of clarity of reading.

The instrument is essentially a milliammeter and hence is quite suitable for voltage measurement. When, however, it is required to measure a current exceeding about half ampere, the instrument is used in conjunction with a shunt (Fig. 9). This shunt is in effect a resistance capable of carrying heavy current without excessive heat being generated. When current passes through the shunt, a potential drop occurs across it which is measured by the moving coil instrument and hence serves as a measure of the current passing through the main circuit. For currents exceeding thirty amperes or thereabouts such shunts are usually placed externally to the instrument and great care must then be taken either to use the shunt leads supplied by the maker or leads of very nearly the same resistance. If this precaution is not taken the correct proportion of the total current will not be shunted and the readings will be unreliable.

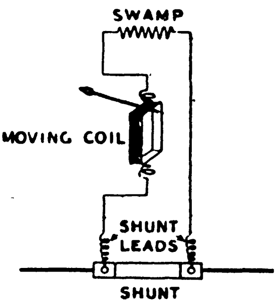


FIG. 9. — CONNECTION DIAGRAM OF MOVING COIL SHUNTED AMMETER.

When the instrument is used to measure voltage, it is usual to insert resistance in series with the moving coil. This resistance may be mounted inside the instrument for voltages up to 600 volts or external to the instrument for higher voltages.

This class of instrument, although it is limited to D.C. measurement (except by special arrangement described later), has a very extensive field of use and is capable of great accuracy and yet at

the same time retains a considerable amount of robustness.

Thermal Type of Instrument.

Although this class is largely confined to the laboratory, it is of interest and is illustrated schematically in Fig. 10. It depends for its operation upon the expansion of a wire usually made of platinum iridium alloy (a), which is heated due to the passage of current through it. The movement is magnified by a system

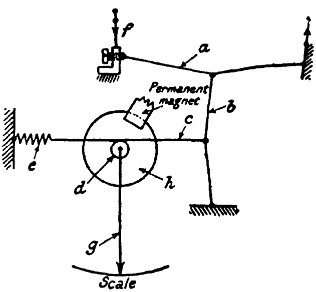


FIG. 10.—DETAILS OF THE THERMAL INSTRUMENT.

This operates on the principle of the expansion in a wire when heated by passing a current through it. The parts of the instrument are: *a*, the heating wire; *b*, phosphor bronze wire; *c*, fine silk ligament; *d*, pulley; *e*, spring; *g*, pointer; *h*, metallic disc.

of levers and transmitted to the pointer (g) by a silk strand (c), which is passed round a pulley (d) coupled to the pointer and fastened to a spring (e). The moving system consisting of the pulley and the pointer is completed by a metallic disc (h) and is suspended in jewelled bearings.

The driving torque is produced by the spring (e) which deflects the pointer as the wire (a) expands due to the passage of current through it.

The control torque is provided by a spiral spring coupled to the moving element.

The damping takes the electro-magnetic form, and is

provided by the disc (*h*) operating in the air gap of the permanent magnet.

The Characteristics of the Thermal Type of Instrument.

Whilst the instrument is relatively simple and cheap to manufacture, it is not extensively used commercially for the following reasons:—

(1) The driving torque being dependent on the heat produced in the wire is proportional to the square of the current, hence the scale is non-linear.

(2) Since the instrument depends upon heat, it is subject to errors due to changes in the ambient air temperatures. A special tension screw (*f*), Fig. 10, is provided to adjust for these changes.

(3) The instrument is sluggish in operation since the wire does not take up its final temperature until a short period of time has elapsed.

(4) The instrument is easily damaged by accidental overloads.

(5) Electrical losses in the thermal instrument are usually heavier than in other classes of instrument.

The most useful field for this instrument is in high frequency circuits such as those used in radio work, because the forces operating it are practically independent of frequency.

Moving Iron Type of Instrument.

This class of instrument is one of the most popular in commercial use since it can be used for both A.C. and D.C. measurement. Fig. 11 illustrates such an instrument schematically. It consists fundamentally of two pieces of specially shaped iron embraced by a

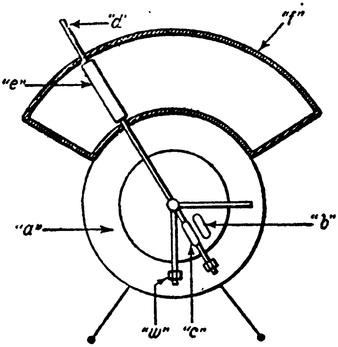


FIG. 11.—ESSENTIAL DETAILS OF THE MOVING IRON AMMETER OR VOLTMETER.
a, coil; *b*, fixed iron; *c*, moving iron; *d*, pointer; *e*, pneumatic damping vane; *f*, cylinder; *w*, weight.

coil (*a*). One iron (*b*) known as the fixed iron is located in a fixed position in the coil, while the other, known as the moving iron (*c*), is suspended in jewelled bearings and is rigidly attached to the pointer (*d*) and the pneumatic damping vane (*e*).

The driving torque is produced by the magnetic force between the two irons, and may take either the form of repulsion or attraction depending upon the particular design.

The control torque can be provided either by means of gravity (Fig. 11 shows this form of control provided by the weight (*w*) attached to the moving element), or by the usual form of spiral control spring.

The damping is pneumatic and is provided by the piston (*e*) moving in the cylinder (*f*).

A Typical Moving Iron Ammeter.

Fig. 12 shows the working parts of a typical 100-ampere moving iron ammeter. The iron vane (A) attached to the spindle, is, when in position inside the coil, opposite a small fixed vane. The current flowing in the winding (of heavy copper strip) magnetises these

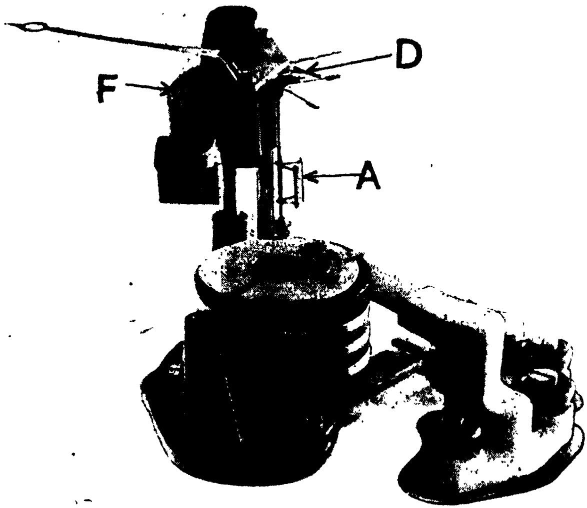


FIG. 12.—A 100-AMP. AMMETER WITH MOVING IRON WITHDRAWN.
A, iron vane; D, flat spiral spring; F, air tight-box.
(*Everett, Edgcumbe & Co., Ltd.*)

two pieces of iron in such a way that they repel one another with a force which increases rapidly with the strength of the current. This repulsion causes the spindle to rotate against an opposing force exerted either by weight (gravity control) or by a flat spiral spring (as shown at D, Fig. 12). The reading therefore depends upon the value of the current, and the scale is marked off in amperes.

Moving Iron Voltmeter

The construction of a voltmeter is similar, except that in place of a winding consisting of a few turns of comparatively large cross-section (Fig. 12) it has a very large number of turns of fine wire, so that the same

deflecting force is obtained with a current of perhaps 1/20 ampere (50 milliamperes). An idle resistance is connected in series with the coil (Fig. 13) so that if the current flowing is 50 milliamperes at full scale, the total resistance of a 250 volt voltmeter would be $20 \times 250 = 5{,}000$ ohms. The idle resistance (or "swamp") should have a resistance many times that of the copper coil, since otherwise the total resistance of the voltmeter will vary with temperature, and its accuracy will be impaired. In the voltmeter shown

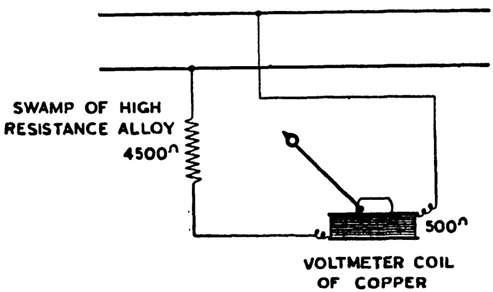


FIG. 13.—CONNECTION DIAGRAM OF MOVING IRON VOLTMETER.

in Fig. 13 the idle series resistance represents 90 per cent of the total, which is a very satisfactory proportion.

The Characteristics of the Moving Iron Type of Instrument.

The main advantages of these instruments are the low initial cost and general robustness of the design. The disadvantage is that they have non-linear scales like the thermal instruments and, furthermore, errors may arise due to wave form, frequency variation and hysteresis. All these errors can, however, be reduced

to small limits by careful design and the non-linearity of the scale can be corrected to some extent by the careful shaping and positioning of the irons with relation to the operating coil.

Dynamometer Type of Instrument.

This class is capable of great accuracy and as a result is largely favoured for laboratory use. It finds little favour as a switchboard instrument, due to the fact that the general construction is rather costly and less robust as compared with other types.

Fundamentally (Fig. 14), the instrument consists of a set of fixed coils (*a*) which surrounds a set of moving coils (*b*). These moving coils are coupled to the pointer (*c*) and the damping vane (*e*), the whole of the moving portion being suspended in jewelled bearings. The instrument is shielded from external fields by enclosing the complete movement in a soft-iron case, which is sometimes laminated.

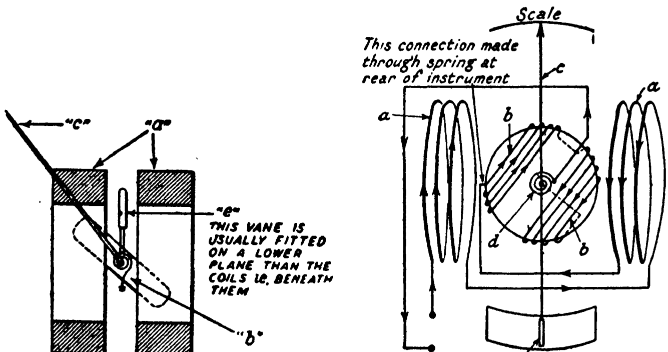


FIG. 14.—THE ESSENTIALS OF THE DYNAMOMETER INSTRUMENT.
Operation depends on the attraction between two sets of coils carrying current. *a*, set of fixed coils; *b*, moving coils; *c*, pointer; *d*, two control springs; *e*, pneumatic damping arrangement.

The driving torque depends upon the interaction of the fluxes caused by the current flowing in the two sets of coils.

The control torque is generally provided by spiral springs which also serve to carry the current into and out of the moving coil.

The damping is generally of the pneumatic form similar to that used in the moving iron type.

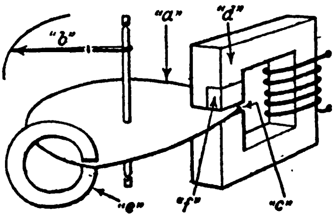
The Characteristics of the Dynamometer Type of Instrument.

As already mentioned, this class is capable of great accuracy being practically independent of wave form and frequency variation; although the instrument reads the R.M.S. value of current, and hence has a non-linear or cramped scale, it is largely used for sub-standards.

Induction Type of Instrument.

This class operates on the principle first outlined by Ferraris. The passage of alternating current through suitably located coils will produce a rotating magnetic field which will interact with a metallic disc suspended near to the coils and causes the disc to rotate. The instrument (Fig. 15) consists of a specially shaped metallic disc (generally made of aluminium or suitable

FIG. 15.
DETAILS OF A MODERN INDUCTION INSTRUMENT.
a, metallic disc; *b*, pointer; *c*, air gap of electromagnet; *d*, electromagnet; *e*, permanent magnet; *f*, shading coil.



alloy) (*a*) coupled to a pointer (*b*) and suspended in jewelled bearings, this disc passes through two air gaps, the first (*c*) located in an electro-magnet (*d*) and the second in a permanent magnet (*e*). The laminations of the electro-magnet are partially embraced by a thick copper loop (*f*) known as a shading coil. This instrument produces the necessary rotating magnetic field required for this type of operation by means of one coil.

The driving torque is produced by the interaction of the eddy currents in the disc with the fluxes emanating from the electro-magnet.

The control torque is obtained from a spiral spring attached to the moving part.

The damping is electro-magnetic, and is provided by interaction between eddy currents in the disc and the flux of the permanent magnet.

The Characteristics of the Induction Type of Instrument.

This instrument is particularly simple and robust, overloads having little permanent effect upon the performance of the instrument. The instrument, like the dynamometer type, reads the R.M.S. value with the same cramped scale. The most serious disadvantages possessed by this class of instrument are the comparatively large errors due to temperature, frequency and wave form variations. These are, however, reduced in modern designs by the use of special alloys and a design of special shunt circuits. At the same time the cramped scale characteristics are improved by a careful shaping of the moving disc.

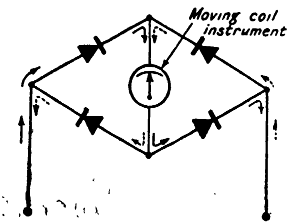
In general this type of instrument is used extensively

for commercial measurement, particularly for the measurement of watts and watthours (see Chapters II and III).

Rectifier Type of Instrument.

This type is a comparatively recent innovation and provides an instrument capable of measuring alternating currents with a linear scale. In effect it is simply a moving coil instrument with the addition of a rectifier which rectifies the alternating current and produces a form of direct current which is capable of

FIG. 16.—A DIAGRAM OF CONNECTIONS SHOWING HOW THE RECTIFIERS ARE CONNECTED TO A MOVING COIL INSTRUMENT TO ENABLE IT TO READ ON AN A.C. CIRCUIT.



being measured by the moving coil instrument. Fig. 16 shows the connections for such an instrument in which the rectifier is connected to give full wave rectification, that is, both positive and negative portions of the wave are utilised for measurement.

The Characteristics of the Rectifier Type.

Apart from the linear scale possessed by this instrument another advantage is the fact that it provides an easy means of obtaining an A.C. milliammeter with a low impedance. Prior to this type of instrument the only low impedance A.C. milliammeter available was the thermo-couple type with its consequent troubles due to overloads.

The principal disadvantage of this class is the error introduced by variation in wave form since the instrument measures the mean value of current, although it is scaled in the R.M.S. value. Such a disadvantage, however, is not serious on most modern supplies since the wave form generally approximates to the sinusoidal.

Electrostatic Type of Instruments.

This class is now generally limited to the laboratory or to some special form of fault indicator. The operation depends upon the electrostatic attraction existing between two plates charged at different potentials; one plate is fixed, while the other, which is coupled to the pointer, is free to rotate on jewelled bearings.

The driving torque is due to the electrostatic force existing between two systems at different potentials.

The control torque is generally provided by a spiral spring or by gravity.

The damping is generally of the pneumatic type.

The Characteristics of the Electrostatic Type of Instrument.

The chief advantage of this type is the small power consumed and hence measurement can be made without upsetting the current distribution of the system. It is interesting to note that in some of the laboratory electrostatic instruments the jewelled bearings are dispensed with and some form of strip suspension to support the moving vanes is used.

Apart from the cramped scale, the chief disadvantage of this class of instrument is the comparatively high

voltage which must be impressed upon the vanes with the consequent source of danger due to breakdown of the instrument. Furthermore, since the operating torque is small, frictional errors sometimes occur. Variations may also be caused by leakage currents.

Apparatus for Measuring High Voltages or Heavy Currents.

It has already been shown that shunts and series resistances are used on D.C. circuits where the values are comparatively high; the equivalent apparatus which is used on A.C. circuits is the transformer (voltage or current), both of which provide a small value of either voltage or current which is proportional to the main value being measured.

Single-phase Connections.

The simple connections for an ammeter and a voltmeter are shown in Fig. 17, which represents a D.C. or

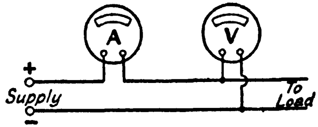


FIG. 17.—HOW AN AMMETER (A) AND VOLTMETER (V) ARE CONNECTED ON D.C. OR SINGLE-PHASE A.C. SUPPLY.

single-phase A.C. supply. It should be noticed that the current is actually taken through the meter for the ammeter, but in the case of the volmeter the meter is connected *across* the mains. This is of course very simple, but there have been cases where an ammeter has been connected across the mains with disastrous results.

Three-phase Connections.

If the load is entirely a three-phase balanced one, it is only necessary to measure the current in one line and the pressure or voltage across any two of the lines. This is shown in Fig. 18 in which the current is measured in line L_1 and the pressure across lines L_1 and L_2. It does not matter however which of the lines are taken for these connections.

With separate single-phase loads, one ammeter

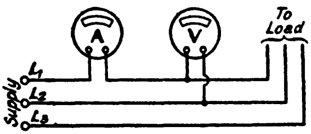


FIG. 18.—DIAGRAM SHOWING CONNECTIONS OF AMMETER AND VOLTMETER ON THREE-PHASE.

should be provided per phase; if voltage is to be measured, one voltmeter would be required, but provided with a change-over switch to check the voltage across each phase.

Connecting the Voltmeter.

As an actual example, the connections for an ammeter and a voltmeter for a 400-volt three-phase motor are given in Fig. 19. It is assumed that a main control switch will be used and this is shown as a three-pole switch and fuse. The connections for the voltmeter are taken from the delivery terminals of this switch-fuse, and it should be noted that in the connection to the voltmeter there is a small fuse. The reason for this is that the wiring to the voltmeter will be of small section cable as the meter will only take a fraction of an ampere. The fuses in the switch-fuse will however carry a comparatively large current

without "blowing," and thus the wiring to the voltmeter might be dangerously overloaded in the event of any kind of short-circuit in the voltmeter circuit. The voltmeter fuse (V.M.F.) prevents the current rising above a very low figure according to the size of the voltmeter.

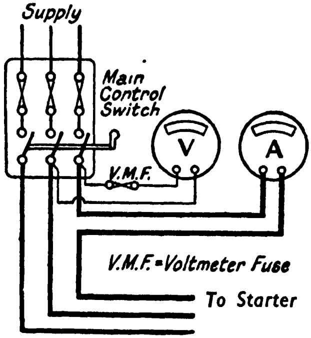


FIG. 19.—ACTUAL CONNECTIONS FOR VOLTMETER AND AMMETER ON A 400-VOLT, THREE-PHASE MOTOR.

Ammeter Connections.

For the ammeter, a lead is taken direct from one of the switch terminals to the meter and then the lead to the motor is taken from the other terminal of the meter. These connections will however be quite clear from the diagram. If it is necessary to install an ammeter in an existing circuit this can be done quite easily by removing one of the leads from the main switch and connecting this up again through the meter, as in Fig. 19. This is sometimes done temporarily in order to check the current taken by a motor and, as will be seen, does not involve any complicated wiring. Many of the troubles experienced with motors would be avoided if an ammeter had been in the circuit, as it will, in most cases, give an indication that everything is not in order. Any sudden increase in current should be looked into unless there is some definite reason for it.

As stated, the connections shown so far are for ordinary voltages of 400 volts or thereabouts and for currents which can safely be taken through an ammeter.

For larger values we have to use (in the case of an ammeter) a *shunt* or (in the case of a voltmeter) a *series resistance*. By using these only a fraction of the current or the voltage is actually put into the meter. In the smaller sizes these resistances are placed inside the meter case and we do not have to take them into account. As we get to the larger range instruments these resistances have to be placed outside the meters on account of size and heat generated.

Connections when Instrument Transformers are Used.

For very high voltages and currents it will be understood that it would be impossible to take direct connections to the meters themselves as they are not designed to withstand voltages of say 6,000 or 11,000 volts. In all cases on E.H.T. systems instrument transformers are used to convert the large currents or pressures to values which can be taken direct to the meters.

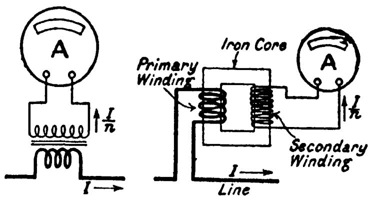
"Straight Through" or Transformer Connected Ammeters.

"Straight through" pattern moving iron ammeters, that is, instruments constructed to carry the total current to be measured, can be obtained up to 600 amps. In spite of this, standard instruments, requiring 0.5, 1 or 5 amps for full scale deflection, are often employed instead of "straight through" instruments. The slight additional cost of the transformer type ammeter is often well worth the saving in trouble of having to lead the heavy current cables up through the meters at the back of the switchboard; the con-

necting cables between the meter and the transformer are of course only of a light guage.

Use of Current Transformer.

The general principles will be seen from Fig. 20 (A), which gives the usual theoretical diagram of a *current transformer*, but the operation will be better understood from Fig. 20 (B). This sketch shows how the actual line current is taken round the primary winding of the transformer. The secondary winding is connected direct to the ammeter and there is thus no direct electrical connection between the line and the



A B

FIG. 20.—HOW A CURRENT TRANSFORMER IS CONNECTED.

$\frac{I}{n}$ is the current in the meter, where n = ratio of transformer.

ammeter. The transformer will be wound so that the current in the secondary winding is some definite fraction of that in the primary winding, as indicated in the diagrams. By this means, using a 100 to 1 transformer, a meter carrying 5 amps. to give full scale reading can be used to measure currents up to $100 \times 5 = 500$ amps.

If, then, a current transformer is used, the actual line connections are taken to the primary winding of the transformer. The terminals of the primary winding will, on account of the heavy current they carry, be very large, while the secondary terminals which have only to carry a few amperes will be very small. For a

current transformer the primary winding consists of a few turns of heavy section, while the secondary will have a larger number of turns of finer wire. The reason for this is that in any transformer the ratio of the currents is the inverse to the ratio of the number of turns on the primary and secondary. For very heavy currents such as those which have to be measured in a large power station the current transformers are merely a number of turns of wire wound round one of the actual busbar connections. They are of course suitably insulated.

Use of the Potential Transformer.

A similar arrangement is used for the voltmeter circuit which employs a *potential transformer*. The diagram for this transformer is shown in Fig. 21 and

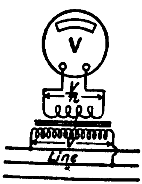


FIG. 21.—HOW A POTENTIAL TRANSFORMER IS USED TO CONNECT A VOLTMETER ON AN E.H.T. SYSTEM.

n = ratio of transformer.

the connections should be compared with those of a current transformer as shown in Fig. 20 (A). For a voltmeter the transformer reduces the voltage from that of the line to a value which can be taken direct to the meter. Thus on a 6,600-volt system the pressure would be transformed to 110 volts, which means that the ratio of transformation must be 6,600 to 110 or 60 to 1.

The primary of a potential transformer is connected across two of the lines, as shown in Fig. 21, while the

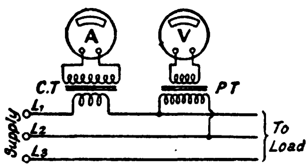
secondary is taken direct to the meter. The primary winding will consist of a large number of turns of fine wire, while the secondary winding will have only a few turns, since the voltage is directly proportional to the number of turns.

It will be understood that the actual construction of a potential transformer is entirely different from that of a current transformer and that they cannot be interchanged.

The actual connections for a three-phase circuit employing both transformers are drawn out in Fig. 22.

FIG. 22.—CONNECTIONS ON THREE-PHASE FOR METERS USING INSTRUMENT TRANSFORMERS.

CT = current transformer; PT = potential transformer.



This shows how the meters are connected with reference to the three lines and will be self-explanatory.

Instrument Terminals.

Whether a switchboard instrument is to have back or front terminals is a small but important point concerning all types. If, say, a voltmeter were specified having terminals to project from its back, quite obviously one must be sure that space exists behind the board on which it is to be mounted for the necessary connections to be made.

With the moving-iron gravity-controlled back-connected type of instrument with single-bolt back fixing, it must also be possible—failing exactness—to provide ample clearance holes in the board for the

projecting terminal stems, in order that the fitter may swivel the instrument at will, until the pointer is seen to be exactly in the zero position. Otherwise, the pointer may be pressing hard over against its spring buffer (denoting faulty mounting) and it would not be a very easy state of affairs to remedy.

As an alternative to back-projecting terminals, front terminals and front fixing should be ordered for instruments not permitting of the conditions just outlined, and, for instance, for mounting flat against a wall.

Range.

Range is an all-important aspect—and most especially so to the man who will use the instrument. "One voltmeter for 500 volts" may be a very concise description, but apart from other points which require clarifying, is one to reckon that the range required is 0-500 volts or that 500 volts is the particular voltage the user desires to measure? Most probably the intention is that a maximum limit of 500 volts should be provided; for in a great many instances the line voltage varying between 400 to 450 is the crucial figure.

Similarly, a 250-volt instrument is generally intended for the nominal phase or line to neutral pressure. However, it is most helpful to define the scale limits desired, especially if some unusual facility is hoped for since there is frequently a certain amount of flexibility in a standard design, an advantage which goes far to reaching the customer's ideal.

So far as switchboard voltmeters are concerned, one is generally interested only in indications within the

bounds of say plus or minus 10 per cent. of nominal value, and, thus, the lower part of the scale calibration which is unavoidably cramped, is no serious disadvantage. On the other hand, this is frequently not so, in the case of the moving-iron ammeter where a double or multi-range has sometimes to be considered.

For example, a higher range of 0-10–100 amperes might be inadequate for the small currents, in which case an additional lower range of 0-1–10 would be justified. Nevertheless, in specifying a double-range switchboard moving-iron ammeter, it is wise to give attention to the alternative method of employing a single-range instrument in conjunction with a transformer, an arrangement which is sometimes cheaper and at times more convenient.

In any event, whatever the specific requirements happen to be, there is no better plan than to get the prospective suppliers, expert as they naturally are, to advocate the most economical method of all to adopt.

When Purchasing Instrument.

The following is a summary of the various points which can with advantage be conveyed to the manufacturer when an engineer has to purchase an instrument.

1. *Type.*—Switchboard or portable? If switchboard, state shape, such as round flush, projecting, or sector, edgewise, horizontal or vertical pattern, etc.

2. *Terminals.*—Say whether connections can be taken in at the back or not, i.e., front or back terminals.

3. *Fixing.*—Would the instrument be mounted on a wall or bolted to a board?

4. A.C. or D.C. or A.C. and D.C.? State voltage of circuit. If A.C.—frequency?

5. *Range.*—If possible state upper and lower limits of expected scale, and any special points which are important.

6. Scale length and accuracy desired.

7. Mention type of circuit in which the instrument will be used.

CHAPTER II

THE MEASUREMENT OF POWER

THE instantaneous power of a circuit is the product of the instantaneous voltage (V) across the circuit and the instantaneous value of the current (I) flowing and may be represented by the formula:—

$$P = V \times I \text{ watts.}$$

In D.C. circuits, this instantaneous value is the same as the steady value under normal stable conditions, but in A.C. circuits the instantaneous values are

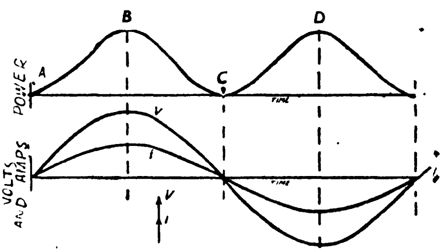


FIG. I. — POWER IN A NON-INDUCTIVE A.C. CIRCUIT.

always changing. For example, referring to Fig. I, which represents the voltage and current waves in an A.C. circuit, the instantaneous power is zero at the instant A, a maximum at the point B, zero at C, and again a maximum at D. It is interesting to note that at the point D the power is still positive, since both the current and voltage are negative and the product will, therefore, be positive. Hence, the power may be represented by the top curve in this diagram.

In this example, the voltage and current waves are super-imposed one on the other and the circuit is said to be at unity power factor. If, however, the current wave is displaced from the voltage, as in the case of a circuit which is inductive or capacitive, then the conditions may be represented by Fig. 2. In this case the top curve represents the power, which it will be seen differs from the power represented in Fig. 1. Actually,

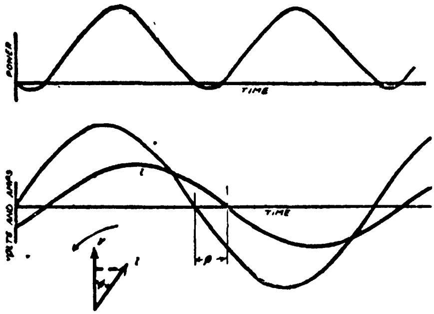


FIG. 2.—POWER IN AN INDUCTIVE A.C. CIRCUIT.

it will now be found that the power is represented by the formula:—

$$P = VI \cos \phi,$$

where ϕ is the angular displacement between voltage and current (see vector diagram).

The Measurement of D.C. and A.C. Power.

Thus, it will be seen that D.C. power can be measured by a voltmeter and an ammeter, but the measurement of A.C. power necessitates a voltmeter, an ammeter and an instrument which reads the phase displacement between the voltage and current.

It is usual, however, in practice to combine all these instruments in a common one, which measures power direct.

Wattmeters.

Fundamentally, a wattmeter has two separate circuits, the one connected across the potential and hence is similar to a voltmeter winding (comparatively high resistance), the other connected in series with the load, and thus is similar to an ammeter winding (comparatively low resistance). Hence the diagram of connections of a wattmeter can be illustrated by Fig. 3.

Two forms of wattmeter are in general use to-day.

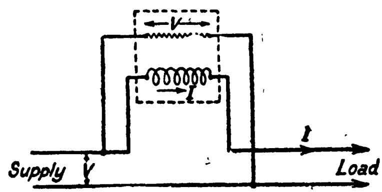


FIG. 3.—HOW A WATTMETER IS CONNECTED IN A CIRCUIT.
Showing the two separate connections, one across the potential and the other in series with the load.

(*a*) The dynamometer type, which is suitable for A.C. or D.C. circuits.

(*b*) The induction type, which is suitable for A.C. circuits only.

Although other types, such as electrostatic, thermal, and moving iron type are occasionally used, their use is so limited that it is not proposed to describe them.

Dynamometer Type Wattmeters

This type of wattmeter is similar in construction to the dynamometer type of ammeter or voltmeter described on page 14 except that the fixed coils are made of a comparatively few turns of heavy section copper to carry the main current of the circuit, whilst the moving coils are made of a comparatively large number of

turns of fine wire having a high resistance similar to a voltmeter winding.

The driving torque depends upon the interaction of the fluxes caused by the currents flowing in the two sets of coils.

The control torque is usually provided by spiral springs which also serve to carry current (proportionate to the voltage across the circuit), into and out of the moving coil.

The damping is generally pneumatic in form, similar to that used on voltmeters and ammeters.

The dynamometer type of instrument is rarely used

FIG. 4.—SHOWING DYNAMOMETER WATTMETER MOVEMENT.
One of the two fixed coils, which carry the current, has been removed and lies on the bench. A spare moving volt coil assembly, with pointer, can also be seen on the bench. The cover of the damping box has been removed. *(Everett, Edgcumbe & Co., Ltd.)*

on switchboards, on account of the comparative costliness and fragility of it when compared with the induction type. It is, however, largely used in the laboratory and test room, where it is used as a standard, both for the measurement of A.C and D.C. power, and also as a transfer standard from one source of energy to the other.

Two forms of this instrument are used, the deflectional and the zero deflection types. The deflectional type is fitted with the usual scale and pointer and the power is read off directly from the pointer and scale. The zero deflectional type is fitted with a torsion head, and a pointer and scale with only a zero mark, and is used where extreme accuracy is necessary. The pointer always being reset to the zero position by means of the torsion head and the power being read as a function of the angle of the torsion head.

Induction Type Wattmeter

This class of instrument differs from the induction voltmeter or ammeter, in so far that two coils are used to produce the rotating magnetic field in place of the one coil with a shading loop. One coil is energised by a current which is proportional to the voltage across the circuit or its equivalent. This coil is made highly inductive so that the current and hence the flux lags 90° behind the voltage.

The second coil is energised by the load current or its equivalent and this coil is made non-inductive so that the current and voltage are in phase. Hence, the two fluxes displaced one from the other by 90°, interact upon the metallic disc or drum suspended near them and cause it to rotate Schematically, the instrument

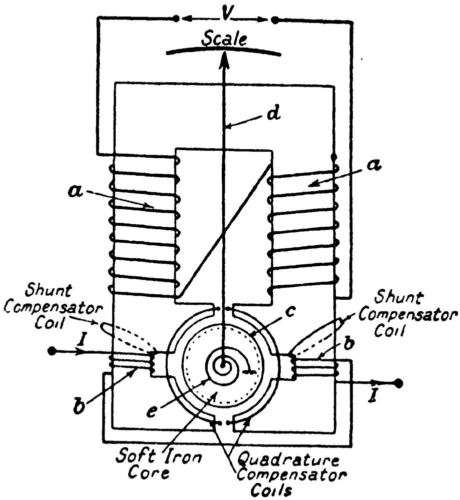


FIG. 5. — THE LAY-OUT OF AN INDUCTION WATTMETER.

The main parts are (*a*) the potential coil, (*b*) the series coil, (*c*) a drum of special alloy coupled to pointer (*d*), and (*e*) control spring.

may be represented by Fig. 5, where *c* represents a metallic drum suspended on jewel bearings in an annular space formed by a soft iron core, and the pole pieces of the combined electro-magnet. The voltage winding is represented by *a* and the current winding by *b*. The drum is to be solidly coupled to a pointer *d* and the requisite control spring *e*. Two additional adjustments are provided in this class of instrument, one termed a shunt compensator and the other a quadrature adjuster. The shunt compensator provides a means of ensuring that the instrument will not indicate with only the voltage coil energised, whilst the quadrature adjuster is added to make sure that a 90° displacement can be obtained between the voltage and current fluxes.

The driving torque is produced by the interaction of

the eddy currents in the drum with the voltage and current fluxes in the electro-magnet.

The control torque is obtained from the spiral spring attached to the moving drum.

The damping is usually electro-magnetic and is provided by a metallic disc coupled to the rotor shaft, and arranged to move in the air gap of a permanent magnet.

The Characteristics of the Induction Type of Wattmeter.

Like the induction voltmeter and ammeter, the instrument is robust and has a large field of application on switchboard instruments.

The most serious disadvantages are a cramped scale, and susceptibility to errors due to temperature, frequency and wave form variations.

When measurements are required on polyphase circuits, it is usual to couple a number of single wattmeter elements to a common rotor system.

Methods of Measuring Power in Polyphase Circuits.

So far only instruments capable of measuring the power in D.C. or single-phase A.C. circuits have been discussed. When polyphase circuits are encountered, different conditions hold, and it is necessary to modify these instruments to obtain true measurements. A knowledge of Blondel's theory is essential before polyphase power measurement can be understood. This theory, without going into the mathematical proof, can be stated as follows:

"If energy is supplied to any system through N wires, the total power in the system is given by the algebraic sum of the readings of N-1 wattmeters."

The theory can easily be understood by referring to Fig. 6, which shows the methods generally used for the more general polyphase circuits encountered in practice, and it might be added that it is usual to couple all these elements together to operate a common

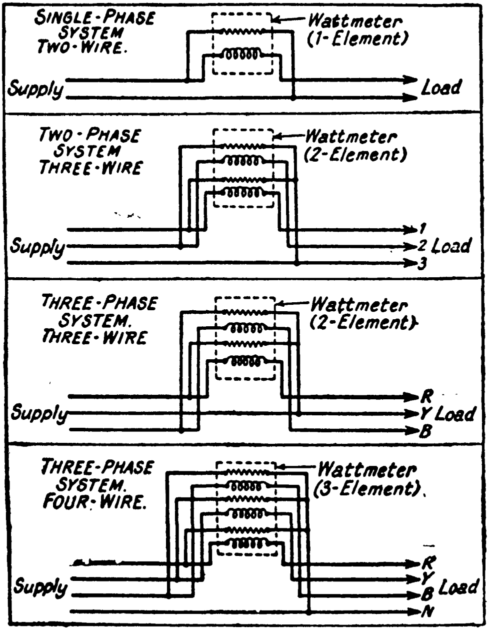


FIG. 6.—METHODS USED TO MEASURE THE POWER IN DIFFERENT KINDS OF CIRCUITS.

indicating device so that the algebraic sum of the elements is obtained automatically.

All the connections illustrated in Fig. 6 provide accurate metering under all conditions of loading; that is, if the currents in the various phases are balanced or unbalanced.

Balanced Load Wattmeters.

There are, however, a number of cases where the phases are balanced and it becomes possible to measure the polyphase power with a number of elements which is less than that stipulated by Blondel's theorem.

It must be understood, however, that these balanced load wattmeters, as they are termed, are only accurate under balanced load conditions; thus, whilst they may be perfectly satisfactory for providing indications of the circuit, they must be judiciously used if the readings are intended for payment purposes.

Under balanced load conditions it is possible to measure the power in a three-phase three-wire circuit with a single element wattmeter in place of the usual two, and the power in a three-phase, four-wire circuit with a single element in place of the usual three elements.

The Connections for Measuring a Three-phase, Three-wire Balanced Load.

Fig. 7 illustrates the connections for measuring a three-phase, three-wire balanced load. It will be seen that two currents are used, the red current and the

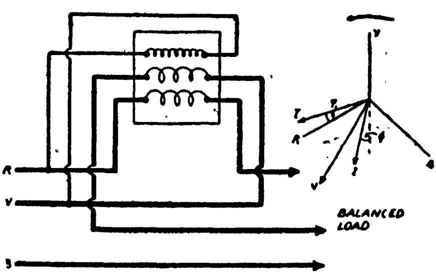


FIG. 7.—THE MEASUREMENT OF POWER IN A THREE-PHASE THREE-WIRE BALANCED-LOAD CIRCUIT.

yellow current reversed, in connection with one voltage, namely, the red to yellow volts.

The Connections for Measuring a Three-phase Four-wire Balanced Load.

Similiarly, Fig. 8 illustrates the connections for a single wattmeter element measuring the power in a three-phase, four-wire circuit under balanced load conditions. In this case, the element is made to

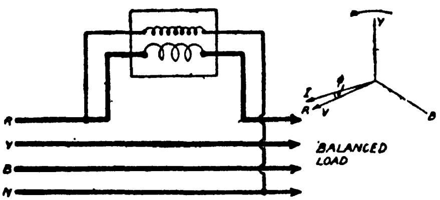


FIG. 8.—THE MEASUREMENT OF POWER IN A THREE-PHASE FOUR-WIRE BALANCED-LOAD CIRCUIT.

measure the power in one phase and the reading is multiplied by three to represent the power flowing in all three phases.

SUMMATION OF TOTAL LOAD

Large consumers of electricity are of course, interested in the value of their total load. Sometimes this can be measured quite easily by the usual methods as in the case where one feeder carries the whole supply. In some cases, however, where more than one feeder is used, it is not so simple.

Fig. 9 is a diagram showing a possible arrangement of feeders in a sub-station belonging to a large consumer. There are two incoming and three outgoing feeders, and the arrangement is such that there is no point in the busbars through which the total load

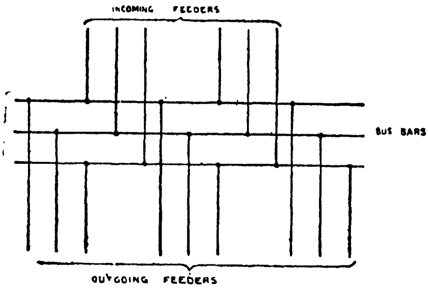


FIG. 9. — TYPICAL ARRANGEMENT OF FEEDERS IN A SUB-STATION BELONGING TO A LARGE CONSUMER.

current flows. It is then necessary to sum up the loads on the two incoming feeders, and to give an indication of the total load on one instrument, either indicating or recording.

A similar case sometimes arises in a generating station, where several machines are feeding into the busbars, and there are a number of feeders connected to these busbars, and the arrangement is again such that there is no point in the busbars through which the total current flows.

There are several methods which can be used for summation of the loads on several circuits. One method is to use a multi-element instrument and another is to connect the secondaries of suitable current transformers in parallel, and so obtain a current proportional to the total load current.

Summation of Multi-element Instruments.

A simple application of the use of a multi-element instrument is illustrated in Fig. 10, which shows the method of summing the total load in two single-phase feeders. To measure the power in a single-phase circuit, a single-element wattmeter with one current and one voltage coil is required. For two such circuits,

therefore, a double-element wattmeter can be used each element measuring the power in one of the circuits.

The current coils are shown connected to the circuits through current transformers, and the voltage coils are shown connected directly to the common busbars. If the range of current is suitable, the current coils can be connected directly in the circuits, and if a high voltage circuit is concerned, the voltage coils can be connected through a voltage transformer.

The two elements of the wattmeter are, of course,

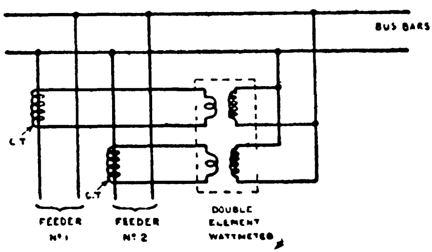


FIG. 10.—SUMMATION OF TWO SINGLE-PHASE FEEDERS BY DOUBLE - ELEMENT WATTMETER.

coupled together, and the instrument gives an indication of the total load. Double element wattmeters are standard instruments, and consequently for this simple case, nothing special in the way of instruments is required. If the number of feeders is three, then a three-element instrument is required, and for any number of feeders, the number of elements is the same as the number of feeders. Instruments having more than two elements, although they are made, are more expensive than the usual single and double element wattmeters.

To Obtain Total Load on this Three-phase Feeder.

If the total load on two three-phase feeders is required, this can also be obtained by the use of a double-

element wattmeter, in which the current coil of each element is wound in two sections. The connections for this arrangement are given in Fig. 11.

The two windings of the current coil in one element are energised from the secondaries of current transformers connected in corresponding lines of the two feeders. This gives the equivalent effect of one current coil carrying a current proportional to the total

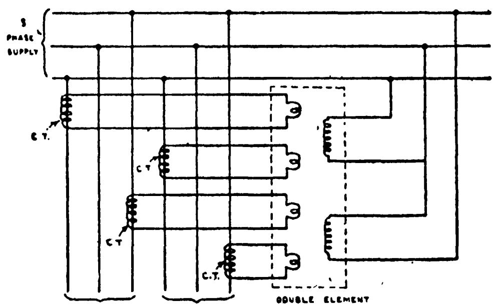


FIG. 11.—SUMMATION OF TWO THREE-PHASE FEEDERS BY DOUBLE-ELEMENT WATTMETER WITH DOUBLE-WOUND CURRENT COILS.

load current. The remaining connections are similar to those of the double-element wattmeter used for three-phase unbalanced load power measurements.

Here again, for more than two feeders, the instrument becomes very complicated and expensive, as the current coils have to be wound in the same number of sections as there are feeders.

The Use of a Four-element Wattmeter.

An alternative method is shown in Fig. 12, in which a four-element wattmeter is used. There are, in effect, two two-element wattmeters, each measuring the total load

paralleled, different deflections would be obtained on the instrument for the same load in kilowatts, depending on whether this load current were flowing through the 600/5 or the 400/5 amps. transformer.

Current Transformers must have same Ratio.

The current transformers then must have the same ratio. This does not mean necessarily the same primary and secondary currents. Besides being able to parallel two transformers of 600/5 amps., say, a transformer 600/5 amps. could be paralleled with one

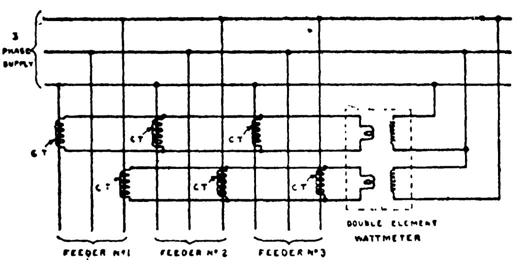


FIG. 14.—SUMMATION OF THREE THREE-PHASE FEEDERS BY PARALLELED CURRENT TRANSFORMERS AND DOUBLE-ELEMENT WATTMETER.

300/2.5 amps. or with one 120/1 amps. The same *ratio* is the important point.

This method can be extended to a number of feeders, but care must be taken if the number is large, as there is a possible source of error. If some of the feeders are not carrying a load at some time, then a magnetising current for their current transformers will be drawn from the total secondary current, and this will cause errors in the instrument readings.

For some four or five feeders, and an indicating or

recording instrument, this error will not be serious, but for integrating instruments where the errors are accumulative, they may be serious, and the method cannot be used.

The connections for this method applied to three three-phase feeders are shown in Fig. 14. An ordinary double-element wattmeter is used, and the current transformers in corresponding lines are connected in parallel and to the current coils of the wattmeter. The connections to the voltage circuits are made in the usual manner for an unbalanced load three-phase wattmeter.

Summation of Separate Supplies.

All the above methods are applicable only to those cases where the circuits in question are connected to a common supply, and therefore have a common voltage or common voltages. It sometimes happens that it is desired to summate the total loads, on circuits which are quite independent of one another, and may be at different voltages, and if alternating current, of different frequencies and numbers of phases. Again reactors are often placed between two sets of busbars in the same station, so that a common voltage supply is not available.

In such cases summation can sometimes be effected by the use of multi-element instruments, but extreme care has to be exercised in such cases, to see that the insulation between elements is high.

Remote Transmission System.

A better method is to use a system of remote transmission, by means of which each load is represented

by some other quantites, such as a number of impulses, or a direct current, the system being such as to lend itself to summation. One such system is the Evershed-Midworth Distant repeater. The transmitter of this system delivers to the repeater circuit, under all conditions, a direct current which is proportional to the original quantity. By connecting the repeater circuits in parallel, a summation can be obtained.

A diagram of connections for the summation of the total load on three separate three-phase circuits is

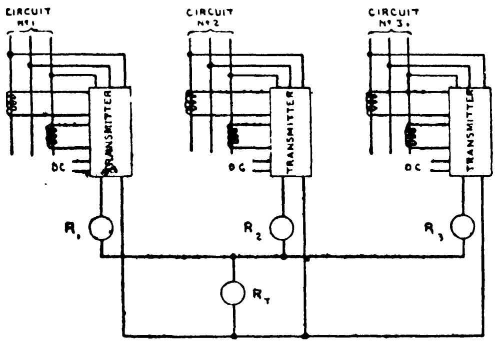


FIG. 15.—SUMMATION OF THREE INDEPENDENT CIRCUITS BY EVERSHED-MIDWORTH DISTANT REPEATER EQUIPMENT.

given in Fig. 15. Each circuit is provided with a transmitter in which the originating movement is a double-element wattmeter.

The repeater circuits from these transmitters are connected in parallel. In Fig. 15, the Receivers R_1, R_2 R_3 indicate the loads on the individual circuits, and the receiver R_T gives the total summated load.

CHAPTER III

THE MEASUREMENT OF ENERGY

SO far, we have discussed the various instruments whereby the engineer can ascertain the state of his network, but none of these instruments are used commercially to levy the actual tariff whereby remuneration is obtained from the community for services rendered.

All tariffs use what is known as the Board of Trade Unit (1,000 watt-hours) as their fundamental basis, and it is the introduction of this time element which has been responsible for the Integrating Meter.

The essential difference between an integrating meter and the indicating type already described is the fact that the former is fitted with some type of register, whereby all instantaneous readings are summed over a definite period of time, whereas the latter indicates the value at the particular instant when it is read.

All commercial integrating meters measure either ampere-hours or watt-hours and it is proposed to divide these into two sections, those used on D.C. supplies and those used on A.C. supplies.

Types of Electricity Meters

The simplest type of meter is that solely intended for D.C. work, measuring only the quantity of current, or ampere-hours. Even this type of meter usually has dials geared to read in kilowatt-hours, on the

assumption that the voltage of supply is approximately constant.

Meters of this type, or energy or watt-hour meters intended solely for D.C. use, are of three main types, which are as follows:

(1) Electrolytic meters, in which the measurement of the current is carried out by the electrolysis of a selected medium in a closed tube.

(2) Clock-type meters, in which one of two similar pendulums swinging side by side is accelerated according to the current consumed while the other is retarded, and a comparison made between their movements.

(3) Motor meters, depending upon the movement of an inductive disc between the pole-pieces of electromagnets.

A.C. meters are usually of the motor type, but A.C. can be measured by types of meter designed solely for D.C. provided that a suitable rectifier is incorporated in the circuit.

A.C. meters can be arranged for single-phase supply, in which case they would also measure three-phase supply if the load were exactly balanced; but as this is an unusual state of affairs, the majority of three-phase meters embody in a single case measuring units for each phase

It may be necessary for A.C. meters, whether single- or three-phase, to be connected to current and voltage transformers, but the mechanism and internal connections are in general the same whether they are intended for supply voltages or use through transformers on high-tension lines.

Electrolytic Meters

The best-known electrolytic meter is illustrated in Fig. 1. It registers the number of units passing through it by the collection in a graduated tube of the particles transferred by the current from a mercury anode through an electrolyte to a specially prepared cathode. Since any electrical current passing through the meter must transfer a quantity of mercury, exactly proportional to the amount of current, from the anode to the cathode, any current however small must be duly registered. With any motor type of meter there is always the possibility that a very small load may not overcome the "stiction" of the motor, so that the meter will not register; but non-starting losses such as these are quite impossible in the electrolytic type of meter.

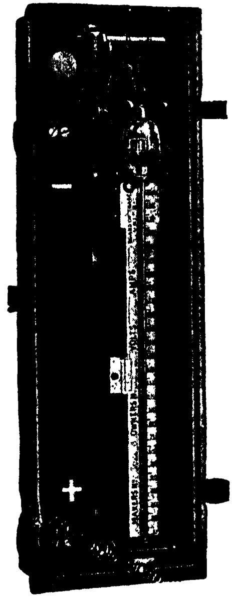


FIG. 1.—SINGLE-TUBE ELECTROLYTIC METER WITHOUT FRONT COVER.
(*Reason Manufacturing Co., Ltd.*)

Other advantages of this type are that it has no moving parts to wear out, no maintenance costs, and no possibility of deterioration through age. When the registering tube of the meter has been filled with deposited mercury, the meter can be reset, which is effected by simply tilting the tube as illustrated in Fig. 2. This returns the mercury to

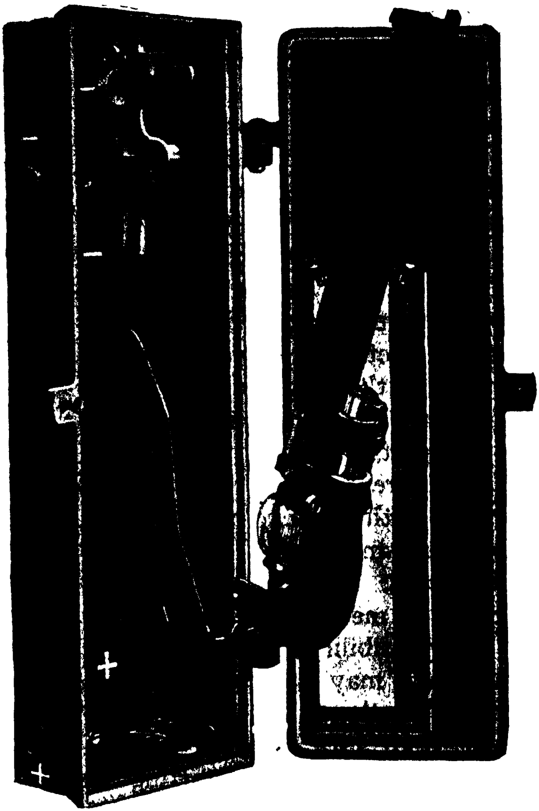


FIG. 2.—METHOD OF RESETTING ELECTROLYTIC METER WITHIN ITS OWN LENGTH.

(Reason Manufacturing Co., Ltd.)

the main tube; a longer interval between resetting can be obtained by the provision of a separate siphon tube, and larger sizes of this type of meter can be scaled up to 500,000 units at one setting.

Fig. 3 shows the diagrammatic arrangement of the

electrical circuit. The electrolytic voltage is obtained by the connection of this part of the circuit across a shunt K, the positive and negative terminals of the instrument being marked E and D respectively. The current flows through a compensating resistance H in series with the electrolytic tube; this resistance is so designed that no changes of temperature affect the accuracy of the meter, an advantage where instruments are required for service in tropical climates. After the compensating resistance the current passes to the anode mercury at right. A glass fence separates this from the cathode C, although both are connected by the electrolyte. The height of the fence is such that there is no risk of the mercury at A

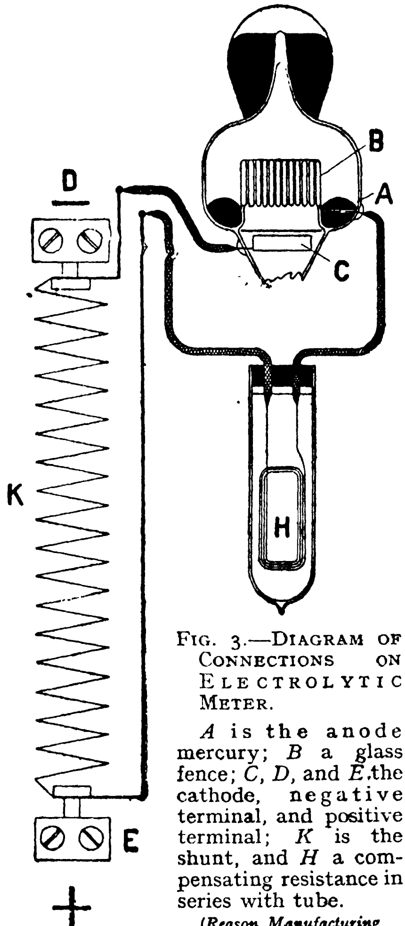


FIG. 3.—DIAGRAM OF CONNECTIONS ON ELECTROLYTIC METER.

A is the anode mercury; *B* a glass fence; *C*, *D*, and *E* the cathode, negative terminal, and positive terminal; *K* is the shunt, and *H* a compensating resistance in series with tube.

(*Reason Manufacturing Co., Ltd.*)

being thrown into the registering tube (not shown in this diagram) by vibration or blows. The registering tube is more clearly seen in Fig. 1.

The small globules of mercury dissociated from the solution by the action of the current are deposited on the cathode, and fall off by gravity into the long narrow tube shown in Fig. 1. This has a scale calibrated in Board of Trade units at the supply voltage on which the meter is to be used.

Fig. 1 shows at the left the shunt or resistance, and at the right the registering tube, with the electrolytic element at the top. Additional anode mercury is seen at the top of Fig. 3; and it will be seen from Fig. 2 that the operation of resetting tilts the mercury from the registering tube back into the position shown at *A*.

Clock-type Electricity Meters.

The Aron clock-type meter records watt-hours, as distinct from electrolytic meters, which measure only ampere-hours. The most prominent feature of the construction of this type of meter is the pair of pendulums with their current coils below them.

The meter depends for its action on the difference in speed of these two pendulums recorded on a set of dials. In the older patterns one pendulum was accelerated by the action of the current, whilst the other oscillated at normal speed under the influence of gravity alone. In the present type greater sensitiveness is obtained by accelerating one pendulum and retarding the other, the change of speed in each case being produced by the magnetic effect of coils carrying the main current on other coils attached to the pendulums and energised by the voltage. The difference

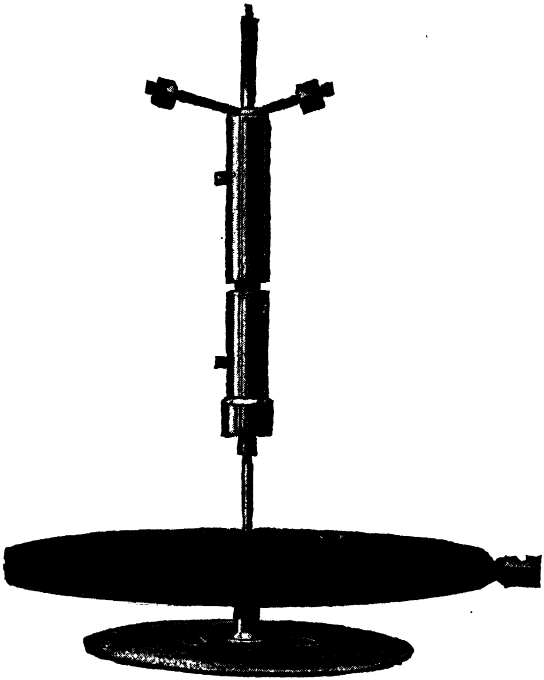


FIG. 4.—DISC AND SPINDLE OF MERCURY MOTOR AMPERE-HOUR METER.
(*Ferranti, Ltd.*)

in speed thus produced is proportional to the watts, and is integrated through the medium of one of the two differential gears contained in the clockwork mechanism.

The Ampere-hour Mercury Motor type Meter.

The mercury motor type meter is used for D.C. circuits. In its simplest form this type of energy meter is generally used as an ampere-hour meter, that is, the instrument actually measures ampere-hours,

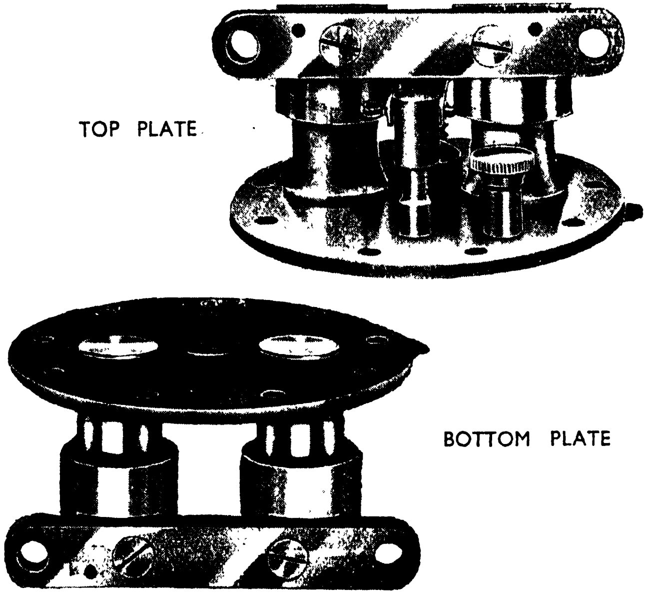


FIG. 4A.—DISMANTLED PARTS OF MERCURY MOTOR AMPERE-HOUR METER.
(*Ferranti, Ltd.*)

although it may be scaled in kilowatt-hours. (It will be realised that the accuracy of this kW.h. reading is based upon the assumption that the voltage of the system remains constant.)

The instrument may be represented schematically by Fig. 6, where (*a*) is a bath of mercury complete with two leads, fitted at two points on the circumference of the bath. One of these leads, the positive one (*b*), is used for the current entry and the second, the negative one (*c*), is used for the current exit. In the bath is a metallic disc (*d*) (usually made of copper), which is coupled to register (*e*). This disc is suspended on a

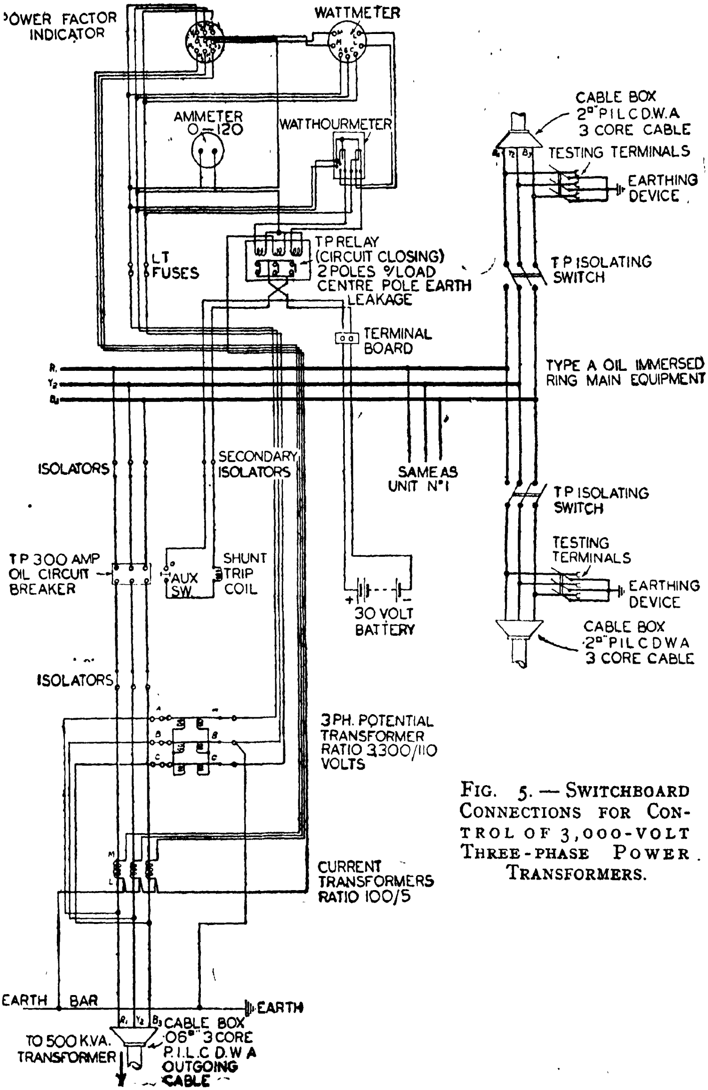


Fig. 5.—Switchboard Connections for Control of 3,000-Volt Three-phase Power Transformers.

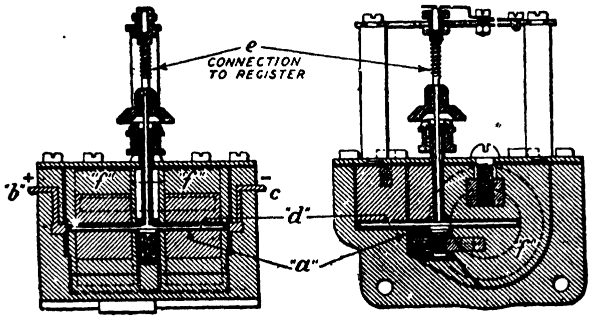


FIG. 6.—DIAGRAM OF A MERCURY MOTOR AMPERE-HOUR METER. (*a*), mercury bath; (b), positive lead; (*c*), negative lead; (*d*), metallic disc; (*e*), register; (*f*), permanent magnet.

jewel bearing so that it will rotate horizontally through the air gaps of a set of powerful permanent magnets (*f*).

The driving torque is produced by the interaction of the current passing through the mercury bath and disc and the field of the permanent magnet or magnets. This torque, which is directly proportional to the current flowing, causes the disc to rotate.

The control or braking torque is produced by the generation of eddy currents in the disc, and is proportional to the speed of the disc, hence under stable conditions the control torque will exactly counterbalance the driving torque, so that a constant speed is maintained, for a constant current and the meter, when fitted with a counter, will measure ampere hours.

Constructional Details.

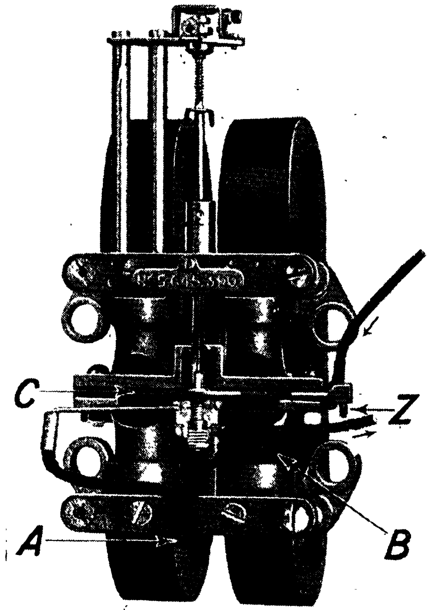
The parts of a typical meter are shown in Fig. 7. They consist of the two permanent magnets, the disc (*C*) and spindle shown inside the ring which forms

the wall of the mercury chamber, and the top and bottom plates which seal off this chamber, the upper one being provided with a mercury filling cap.

The rotating disc is of copper and is submerged in the mercury, its buoyancy being adjusted by a cylindrical weight on the spindle. The pressure on the

FIG. 7.—SECTIONAL VIEW OF THE FERRANTI TYPE F.H. MERCURY AMPERE-HOUR METER.

A and B are the compensating coils, C is the disc and Z the positive terminal.



jewelled bearing is thus reduced to the least possible amount, and the mercury also acts as a cushion in preventing damage to the jewels from sudden shocks. The two metal plates at the top and bottom of the mercury bath are insulated on their inner sides, and the wall of the bath is also of insulating material. The

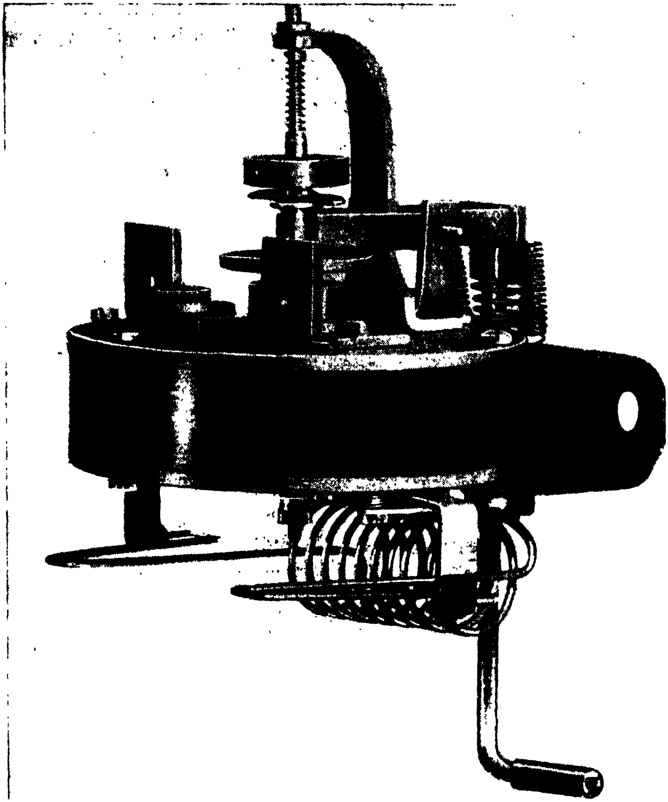


FIG. 8.—A COMPACT TYPE OF MERCURY MOTOR METER.
The coil shown beneath the mercury bath is the shunt.
(*Measurement Ltd.*)

terminal (*Z*) by which the current enters can be seen at the right-hand side of the insulating ring.

There are two compensating coils *A* and *B*. One is shown in Fig. 7, wound round the steel bar coupling

the lower pair of pole-pieces. It overcomes the effect of mercury friction, which increases with the speed. It increases the driving flux. It also increases the retarding flux in one magnet but decreases it in the other by a corresponding amount, and thus the total retarding torque remains the same. This compensating coil is so adjusted that the driving torque is increased by an amount corresponding to the increased friction. The other compensating coil is also visible, wound round the right-hand pole-piece of the lower pair. It counteracts the effect on the magnets of external short-circuits.

Another type of mercury meter is shown in Fig. 8. In this meter a cobalt-steel magnet has been used, so small as to be located entirely within a shallow copper bell instead of a disc, which is used as a rotor. The magnetic circuit is completed by a steel ring.

The steel ring surrounds the bell and forms the wall of the mercury chamber, and is insulated by means of a special glass-smooth varnish. The ring is closed at the top and bottom by means of heavily nickelled brass plates, the lower one of which carries the magnet and also two insulated contacts diametrically disposed along the axis of the magnet.

The current path is from one of the two contacts vertically upwards through the rim of the bell, across the top plate, and vertically downward through the bell again, passing out through the second contact. It will be seen, therefore, that the current has to traverse the magnetic flux twice, that is, on its upward and downward paths through the bell.

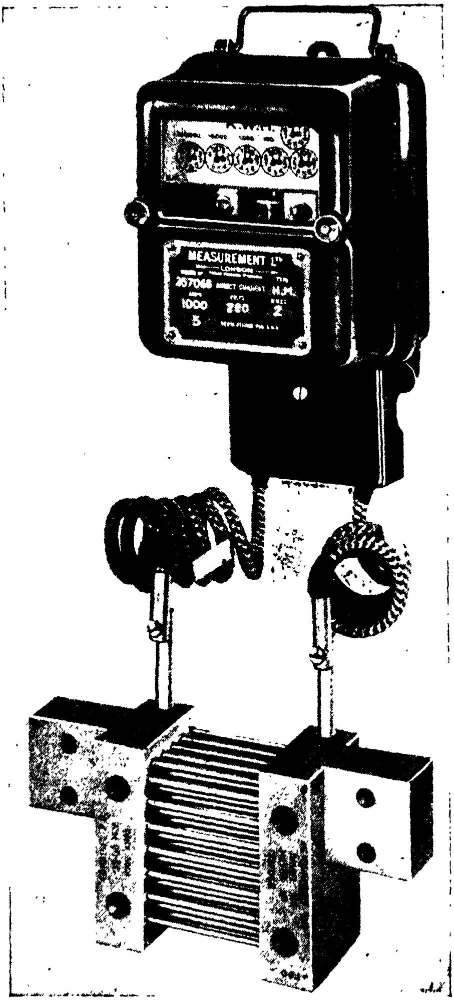


FIG 9.—D.C. AMPERE-HOUR METER WITH EXTERNAL 1,000-AMP. SHUNT.
(*Measurement Ltd.*)

Shunts for Measuring Heavy Currents.

The coil shown beneath the mercury motor is the shunt for small currents; for larger currents up to 1,000 amps. the shunt is supplied separately or in an extended compartment of the meter casing. Above 1,000 amps. the shunt is quite separate, and a large shunt of this type is illustrated in Fig. 9.

Characteristics of the Mercury Motor Ampere-hour Meter.

The most serious errors of

this type of meter are due to friction and temperature. These frictional errors occur both at heavy and light loads. At heavy loads the error is mainly due to fluid friction between the disc and the mercury, but this is reduced in practice by keeping the full-load speed of the motor low, at the same time using a high driving torque and braking torque.

The friction at low loads, due to bearing friction and skin friction between the disc shaft and the mercury, is minimised in practice by the use of carefully designed jewel bearings and a small diameter rotor shaft.

The temperature errors can be reduced to small limits by the use of a special alloy, which is placed near the poles of the permanent magnets. This alloy has a permeability which varies with temperature and provides compensation for the change in disc resistance due to temperature.

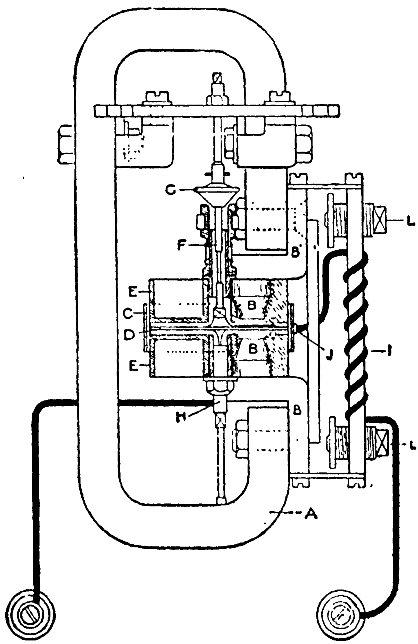


FIG. 10.—CROSS-SECTION OF CHAMBERLAIN AND HOOKHAM SINGLE MAGNET TYPE AMPERE-HOUR MERCURY MOTOR METER.

Registering Mechanism.

Whether a meter registers ampere-hours or watt-hours, all dials are marked in kilowatt-hours; the registering mechanism may be of the pointer type, or of the jumping-figure cyclometer type. The spindle of the motor is connected to the registering train of wheels by a worm on the spindle; the whole of the registering mechanism can be withdrawn merely by removing two screws, the mechanism being as easily replaced.

Cyclometer-reading dials may be of the roller type, or the disc type.

D.C. Watt-hour Mercury Meters.

Since the ampere-hour meter will only measure kilowatt-hours accurately under constant voltage conditions, it must be modified by the introduction of a voltage element before it can be used on a circuit where the voltage fluctuates.

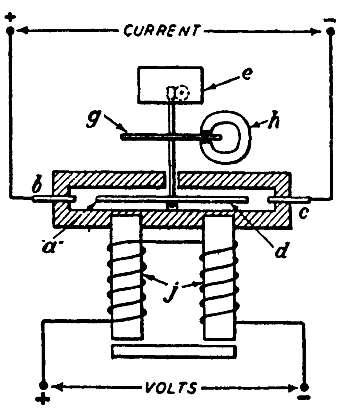


FIG. 11.—DIAGRAM OF MERCURY MOTOR WATT-HOUR METER.

Such an instrument is represented schematically in Fig. 11, where (*a*) is the mercury bath complete with the two current leads (*b*) and (*c*) mounted in the circumference of the bath, (*d*) is the driving disc coupled solidly to a second disc (*g*) external to the mercury bath, and a

counter (*e*). The permanent magnets mentioned in the description of the ampere-hour meter are now replaced by an electro-magnet (*j*) which is energised by the voltage across the circuit.

The driving torque is due to the interaction of the current passing through the disc (*d*) and the field from the electro-magnet (*j*) and is proportional to the power of the circuit (product of current and voltage).

The braking torque is provided by the eddy currents generated in the disc (*g*) by the permanent magnet (*h*).

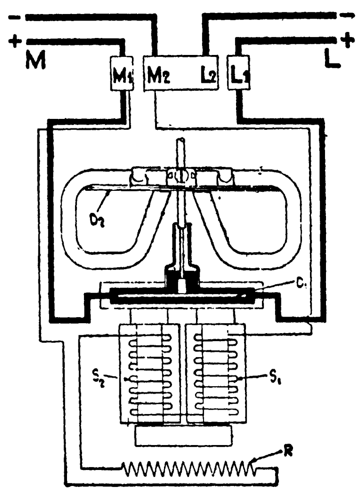


FIG. 12.—DIAGRAM OF CONNECTIONS OF D.C. WATT-HOUR METER.

The current passes by means of the heavy conductors through the mercury bath; the voltage coils are shown at *S*2 and *S*1 on the electro-magnet; the upper electro-magnet acts as a brake on the disc on the same spindle as that enclosed in the mercury bath.

(*Ferranti Ltd.*)

A diagram of connections of such a watt-hour meter is shown in Fig. 12. The driving disc *D*, completely immersed in mercury, is mounted above a strong elctro-magnet, excited by the shunt coils S_1 and S_2 connected across the mains. The brake disc D_2 is mounted on the same spindle and rotates in the gap of the permanent magnets.

The main current passes from terminal $M1$ through the mercury and disc to the terminal $L1$; the shunt current passes from $M1$ through the shunt coils and a resistance R to the terminals $M2$, $L2$.

The current through the disc D_1 is the load current to be measured, and the current through the shunt coils S_1 and S_2 is proportional to the voltage of the supply. The interaction between the load current through the disc and the flux from the electro-magnet exerts a driving torque on the disc D_1, causing it to rotate.

The driving torque in this type of meter will be proportional not only to the current passing through the meter, but to the voltage of the supply; that is, to the *watts* passing through the meter. Eddy currents in the disc D_1 are reduced to a suitable minimum by a number of radial slots.

Construction of D.C. Watt-hour Meter.

Fig. 13 provides a section of a similar type of meter motor. The copper disc is shown at A in its mercury bath. The magnetic field is set up by the two shunt coils on the electro-magnet K located immediately beneath the armature; the flux cuts twice through the armature A, the magnetic circuit being completed through an iron ring Q placed immediately above the armature. A ring of insulating material W is placed between the upper and lower portions of the mercury chamber and carries the two terminals X, X, by means of which the current is conveyed to and from the armature. The mercury in which the armature is immersed forms the connection between the terminals X, X, and the periphery of the armature. If the meter

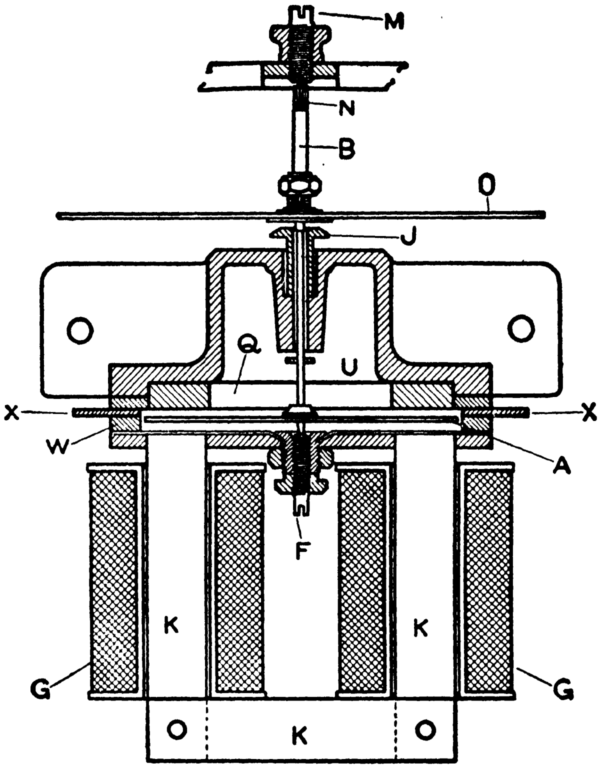


FIG. 13.—SECTION OF D.C. WATT-HOUR METER.

The terminals to the mercury bath are shown at *XX*; *K* is the electro-magnet, and *G* the shunt windings; *O* is the brake disc.

(*Chamberlain & Hookham Ltd.*)

is inverted or laid on its back no mercury can escape, as the mercury chamber is constructed on the well-known principle of the unspillable inkwell. It is possible, however, if the meter is violently shaken, for mercury to be ejected, and to guard against this contingency

during transit a flat forked spring is pushed under the brake disc *O*, lifting the valve *J* into contact with a leather washer fixed to the under side of the brake disc. This spring may be removed after the meter reaches its destination. The armature and brake disc are fixed on a vertical spindle *B*, the lower end of which rests on a jewelled bearing set in the screw *F*, and the upper end carries the driving pinion *N*. The speed of rotation of the armature is proportional to the current passing through it and to the strength of the field in which it rotates. The speed is adjusted by means of a brake magnet acting on the aluminium brake disc *O*.

Single-phase A.C. Induction Meter.

The induction watt-hour meter is practically universal for measuring energy in A.C. circuits. The

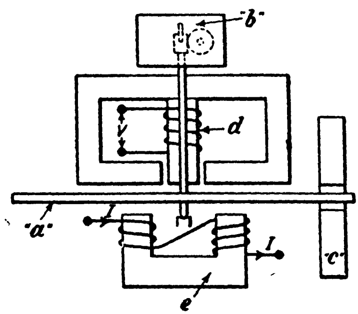


FIG. 14.—DIAGRAM SHOWING ESSENTIAL PARTS OF INDUCTION WATT-HOUR METER.

The essential parts are: (*a*) metallic disc; (*b*) counter; (*c*) braking permanent. Voltage winding (*d*) and current winding (*e*) of electro-magnet.

meter may be represented in the simplest single-phase form by Fig. 14. It consists of a metallic disc (*a*) supported by a jewel bearing at the bottom end and restrained by a spring journal bearing at the top end. It is interesting to note that the axis of rotation for both D.C. and A.C. energy meters is

vertical, whereas most of the indicating instruments, already described, for switchboard work possess a horizontal axis of rotation. The jewel bearing of the energy meter has therefore a cup shape, as compared with the V shape generally used for indicating instruments. The disc (*a*), which is coupled to a counter (*b*), rotates in two air gaps, one belonging to a braking permanent magnet (*c*) and the second belonging to the combined electro-magnet, which carries the voltage winding (*d*) and the current winding (*e*).

Apart from these fundamentals, it is usual to fit the

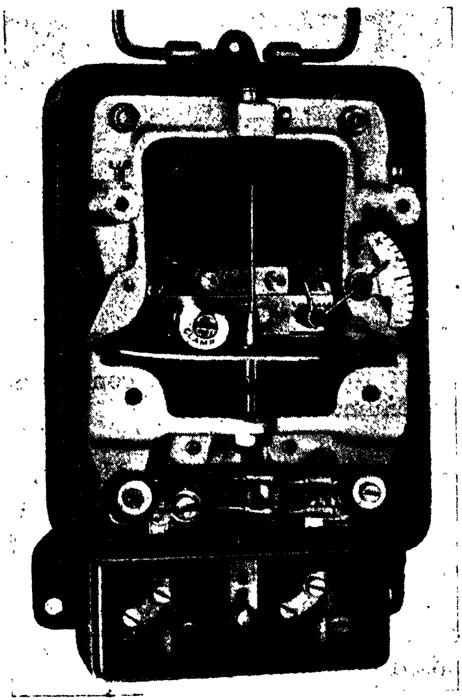


FIG. 15.
SINGLE-PHASE INDUCTION METER.

The voltage coil is visible at the back above the driving disc, which is also the brake disc. Current coils are shown below; the two large magnets in front of the right-hand illustration are the brake magnets.

(Metropolitan-Vickers Electrical Co. Ltd.)

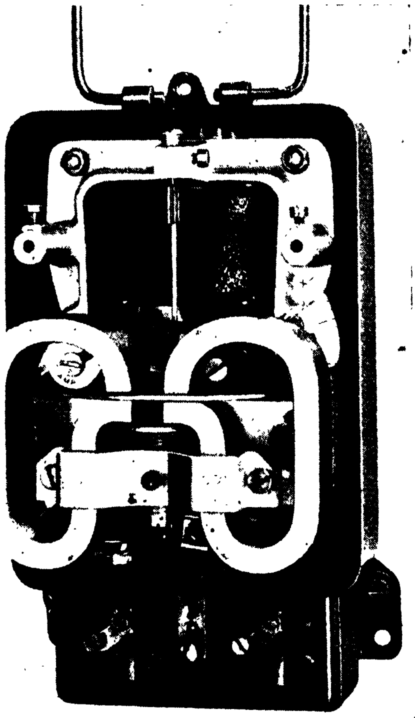


FIG. 16.—ANOTHER VIEW OF SINGLE-PHASE INDUCTION METER.

meter with a number of compensating devices which are enumerated below.

Adjustment of Induction Meters.

Figs. 15 and 16 provide two views of a single-phase induction meter, from which most of the working parts can be clearly seen.

Speed is adjusted by a magnetic shunt applied to the magnets, illustrated in Fig. 17. The shunt can be raised or lowered respectively to increase or decrease

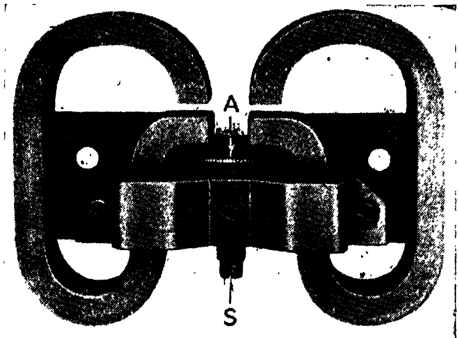


FIG. 17.—BRAKE-MAGNET SYSTEM.
The magnetic shunt *A* is operated by means of shank *S*.
(*Metropolitan-Vickers Electrical Co., Ltd.*)

the speed, and can be locked in position by means of a small central screw. Further adjustment may be made by moving the entire magnetic system, inwards to increase or outwards to decrease the speed. Two tension and four compression screws are provided for this purpose.

Low-load adjustments may be made by moving a metal loop across the face of the voltage magnet pole by means of a rack and pinion operated by a screw-driver. Clockwise rotation of the screw decreases the low-load speed. This adjustment is necessary on account of the increased effect of friction at very light loads.

Adjustment of the meter on inductive load is effected by moving a clamp along a resistance loop; movement to the left increases the speed on inductive load. The clamping should be tightened after adjustment by means of the screw.

Another type of single-phase A.C. meter element is

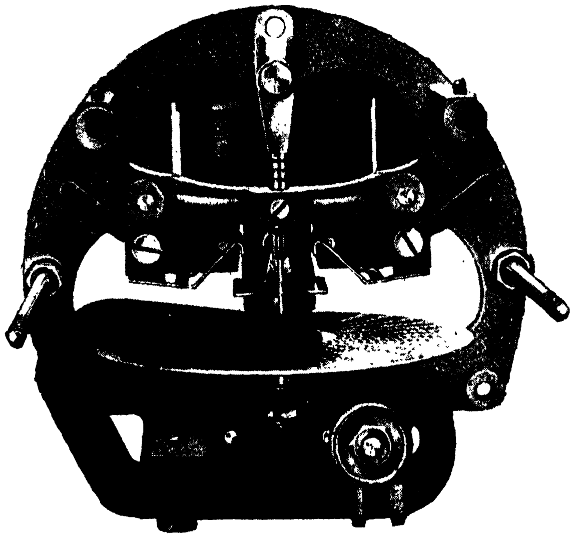


FIG. 18.—A.C. MOTOR METER ELEMENT—FRONT VIEW.
(*Metropolitan-Vickers Electrical Co., Ltd.*)

illustrated in a compact form in Fig. 18, which shows a front view of the element, with the voltage coil above and the current coil below, as previously described. Speed adjustment of this type of meter is made by a prominently placed thumb-nut which gives micrometer adjustment of the brake magnet; this is shown at the foot on the right of Fig. 18.

Light-load adjustment is obtained by two metal loops placed on either side of the centre limb of the voltage electro-magnet. The loops are pivoted at front and back to move freely in the gaps and are secured by clamp screws. A metal loop is fitted round the centre limb to correct for power-factor adjustment on inductive loads; raising this loop increases registra-

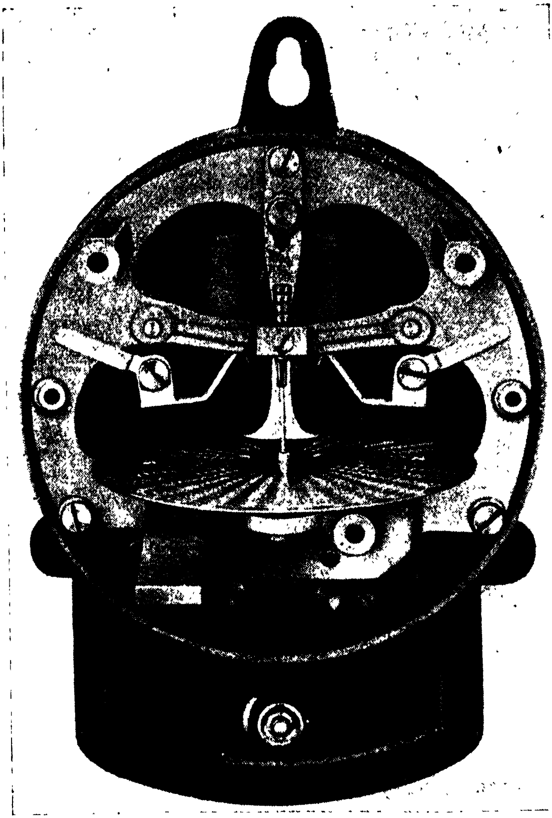


FIG. 19.—INTERIOR OF SAME METER AS IN FIG. 18.

This illustration shows the central loops for power-factor adjustment, and the two side loops for light-load adjustment.

(Metropolitan-Vickers Electrical Co., Ltd.)

tion on lagging power factor. The power-factor loop and the two side loops for light-load adjustment are shown in Fig. 19.

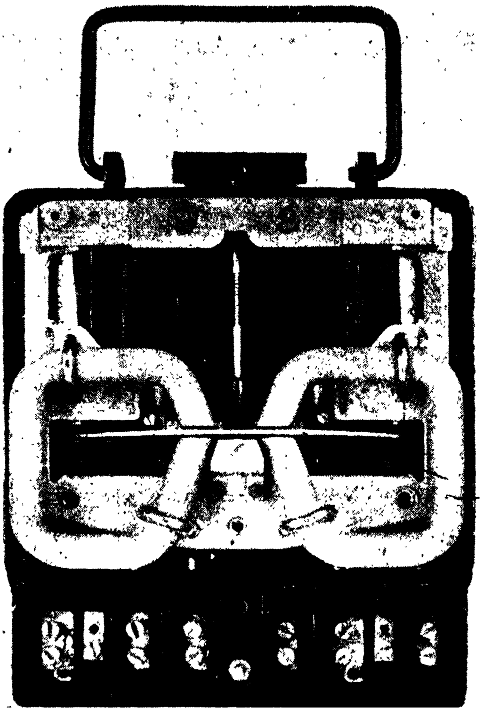


FIG. 20.—POLYPHASE METER.

The brake magnets are seen in front, and above each of them, the ends of the voltage coils.

(*Ferranti Ltd.*)

POLYPHASE kWh. METERS

Blondel's theorem (referred to on page 35) applies to the measurement of energy in a similar manner to the measurement of power, hence N—1 watt-hour meter elements will always measure the energy supplied through N wires. The polyphase meter simply consists

of a number of elements operating on a common rotor system, coupled to a single counting mechanism.

Single-Disc Instrument.

One of the simplest three-phase instruments is shown in Fig. 20. In the front are seen the brake magnets, and immediately behind them the ends of two coils, in the arrangement required for a three-phase, three-wire system.

Neglecting the possible insertion in the circuit of current and voltage transformers, the arrangement of these coils would be as shown in the diagram of connections in Fig. 21. Fig. 22 shows a corresponding diagram for three-phase, four-wire supply. It will be seen from these two diagrams that in one case two meter movements and in the other three meter movements, are necessary.

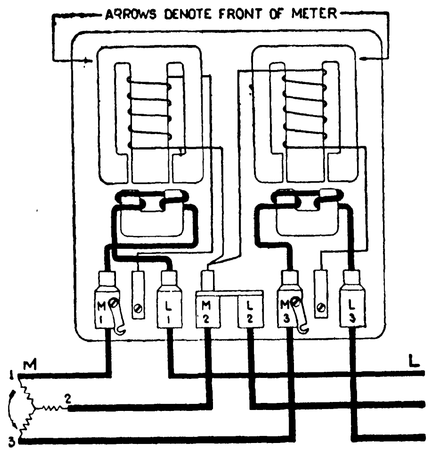


FIG. 21.—DIAGRAM OF CONNECTIONS FOR THREE-PHASE THREE-WIRE A.C. METER.
(*Ferranti Ltd.*)

Arrangements of two coils is indicated in Fig. 20, and the current coils can be seen beneath the disc and in the space enclosed by the magnets. If, however, a third set of coils were necessary, it would have to be placed at the back of the meter case, opposite to the

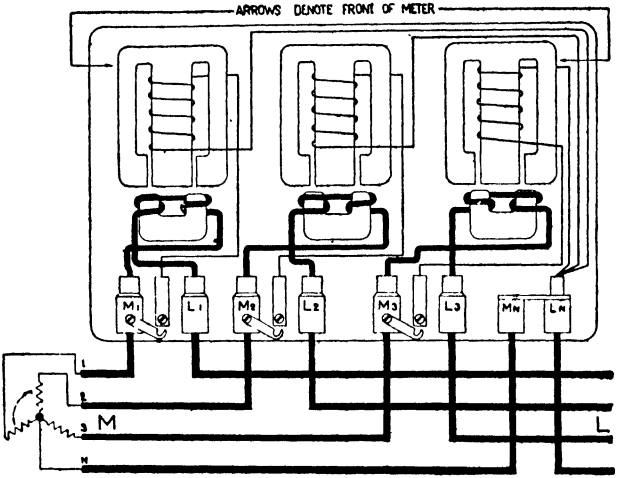


FIG. 22.—DIAGRAM OF CONNECTIONS FOR THREE-PHASE FOUR-WIRE A.C. METER.

(Ferranti Ltd.)

position occupied by the magnets. The two coils, or in a four-wire system the three coils, are all driving a single disc.

Two or Three Disc Instruments.

While the same diagram of connections would apply, since all polyphase meters have two or three movements, the coils are frequently arranged to operate upon two discs or three discs mounted upon the same shaft. An example of this type of meter is shown in Fig. 23; while this meter is much larger in size than that previously described, it is claimed that with the three-disc arrangement there is less risk of interaction between the driving elements.

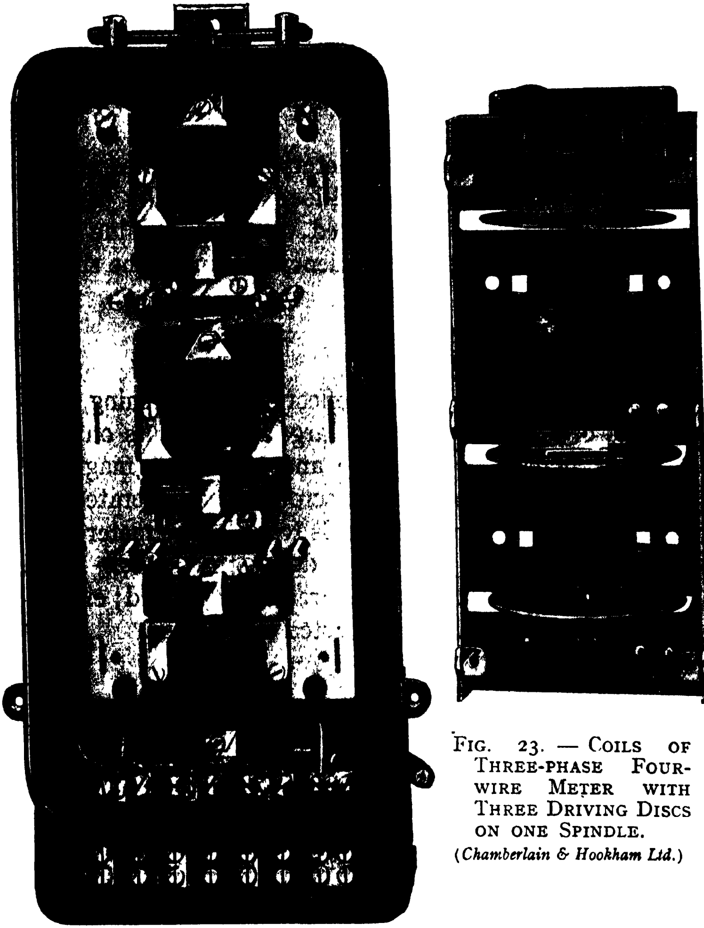


FIG. 23. — COILS OF THREE-PHASE FOUR-WIRE METER WITH THREE DRIVING DISCS ON ONE SPINDLE.
(*Chamberlain & Hookham Ltd.*)

Adjustments of Polyphase Meters.

Shunt running, or the driving of the disc when no current is flowing by means of the voltage coil alone, is prevented on these and other meters by means of two holes punched in diametrically opposite points of the

discs. When either of the holes comes underneath the shunt electro-magnet a slight locking effect is produced, sufficient to prevent more than half a revolution on the shunt alone.

The starting current of meters such as these is less than 0.5 per cent of the full-load current; by careful adjustment it can be reduced to a lower value still without introducing any tendency to run on the shunt alone.

Full-load Adjustment.

Full-load adjustment is effected by loosening, by means of a screwdriver, the large locking-nuts on the magnet brackets seen above and below the magnets in Fig. 24. The micrometer screw is then operated so that the magnets move inwards to make the meter run faster or outwards to slow down the speed. The locking-nuts should then be carefully tightened; either or both magnets may be adjusted as required.

Low-load Adjustment.

Low-load adjustment is provided on the centre phase, as will be seen marked on the screw immediately above the disc in Fig. 24. The screw engages with metal screens located immediately beneath the pressure electro-magnets, and arrows indicate the direction in which the screws should be moved for increase or decrease of speed.

Inductive-load effects are controlled by the movement of three screens placed on the centre limbs of the three pressure electro-magnets. The movement of these screens is controlled by a similar screw marked IND LOAD PH2; slackening the screws clamping the

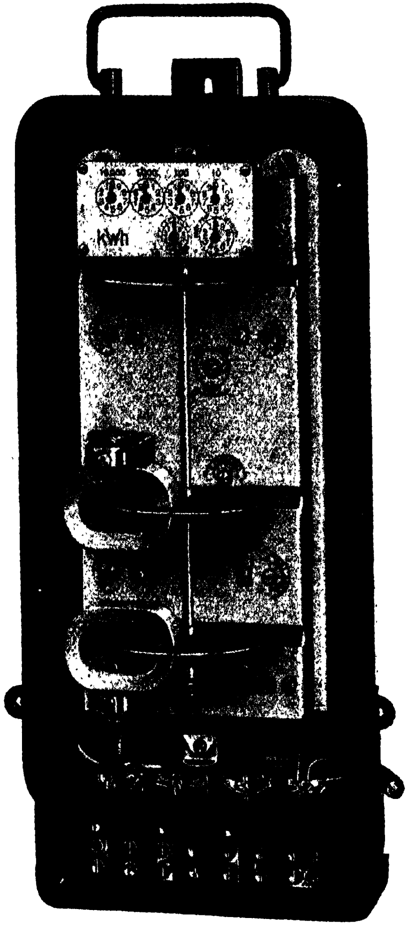


FIG. 24.—MEANS OF ADJUSTMENT OF THREE-PHASE FOUR-WIRE METER.

(Chamberlain & Hookham Ltd.)

scaled plates on the top and bottom elements enables the adjustment to be readily made from this screw. It is operated by rack and pinion.

Torque Balancing Arrangement.

Balance of the elements is effected from the front of the cover by means of clearly marked screws; the middle element is regarded as standard and the top and bottom elements are matched to it one at a time.

In effect this polyphase meter consists of three single-phase meters, and the adjustment for any one unit will therefore correspond to those for an A.C. meter previously described. Another advantage of this type of meter is that no special stocks of spares need be kept, as the parts which may require replacing are those which are standard for single-phase meters.

Two-rate Meters.

Whether a meter is intended for use on continuous current or A.C. circuits, it may be necessary for current to be charged at different rates in the daytime as compared to that at night. If advantage is taken of the lower rate in the evening, by the use of the heavier load at a time when the price is less, there will be a tendency to even out the load on the power station and thus use the plant more economically. One of the most important uses of the two-rate system is in storage-water heating, where the heater, working on the low-price rate, heats up water in a heavily laged cylinder, for use later on.

There is no change whatever in the construction and working of the meter to which this mechanism is applied. The two-rate device is operated by an external time switch which throws over the connection between spindle and dial from one train of wheels to another. Two-rate meters therefore have two series of

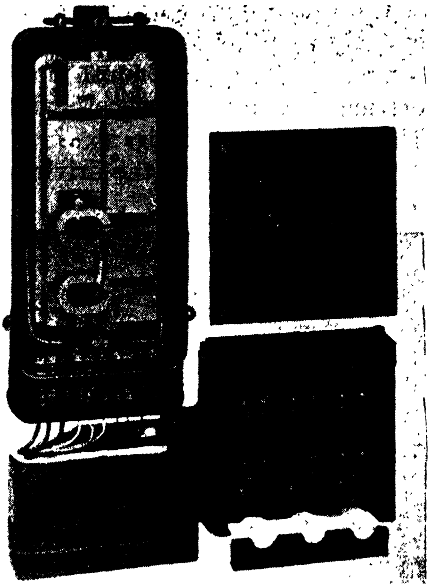


FIG. 25.—INTERIOR VIEW OF 100 AMP. CHAMBERLAIN AND HOOKHAM "TRANSFORMETER" FOR USE ON THREE-PHASE FOUR-WIRE SYSTEM.

Showing meter and current transformer box. The transformer unit can be located on either side or bottom of the meter.

(General Electric Co., Ltd.)

dials, labelled high scale and low scale, with a pointer showing which scale is in use at any moment.

Time Switches.

The change-over mechanism is operated by a time switch, consisting in effect of an electric clock with two contacts, which operate the change-over at specified hours according to the setting.

A time switch can be operated by a synchronous-motor clock, with a mechanism similar to that of electric clocks, or by a clock driven by a spring, the spring being wound up by a synchronous motor. If the electricity supply should fail, the spring will keep the clock going for 36 hours.

The simplest form of time switch does not, however, embody a spring mechanism; and in this case it will consist of a synchronous motor used as a clock driving the train of wheels which changes the rate. This is illustrated in Fig. 26.

The connections to the driving motor and gears are

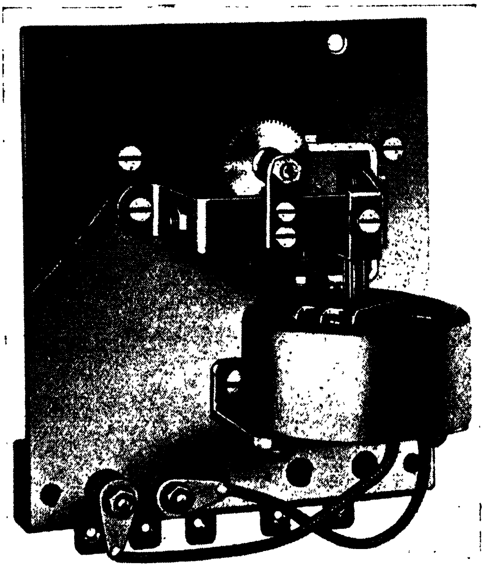


FIG. 26. — TIME SWITCH WITH SYNCHRONOUS MOTOR.
(*Metropolitan-Vickers Electrical Co., Ltd.*)

clearly seen from this figure. The speed of the motor is 200 R.P.M; it consists of a laminated electro-magnet having shaded poles and a plain cylindrical copper bell rotor, an iron core being fixed between the poles. Adjustment of the driving torque can be made easily by lowering the rotor bell on this shaft to increase the torque, or vice versa.

THE MEASUREMENT OF MAXIMUM DEMAND, KILOVOLTAMPERE-HOURS, AND REACTIVE kVAh

For small consumers, such as domestic premises, two forms of tariff are usually employed. The simplest is that in which a charge is made per unit (kilowatt hour) supplied, while the other is known as a two-part tariff. In this a fixed charge is made per annum plus a charge per unit supplied. This fixed charge may be based on the rateable value of the premises or the floor area, and is intended to cover the cost of providing the supply, while the charge per unit covers the cost of the actual energy supplied.

Strictly speaking, the fixed charge per annum should be based on the maximum load which the consumer imposes on the supply, but with small consumers the measurement of this maximum demand would be rather troublesome, and it would be difficult to explain to non-technical consumers the reasons for such a charge and the method by which it is measured.

For both kinds of domestic tariff then it is only necessary to meter the actual units supplied and for this purpose standard kilowatt-hour meters are employed.

Importance of Maximum Demand with Large Consumers.

When dealing with large consumers, such as factories, the question of the maximum load which may be taken is of considerable importance, since the supply company must have machines and cables capable of dealing with this maximum load.

The matter is not, however, quite so simple as a determination simply of the maximum load or demand. It is clear that a demand, say, of 1,000 kW. for a period of two seconds would not cause the supply company any concern, whereas a demand of 500 kW. for 15 minutes would have to be taken into account in connection with the supply.

The Duration of Maximum Demand is also important.

The time for which the demand lasts is, therefore, as important as the value of the demand, and this time must accordingly enter into any true determination of the maximum demand.

For this reason it is usual to average the demand over a predetermined interval of time, such as half an

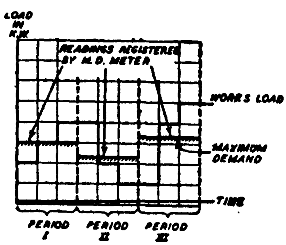


FIG. 27.—SHOWING METHOD OF OBTAINING MAXIMUM DEMAND READING.

This diagram represents a particular load divided into equal time periods. Period III is the period of maximum demand.

hour, and to take the maximum of these average values as the true maximum.

A Typical Example.

Suppose, for example, the time period chosen is 30 minutes, and that the load during the first 5 minutes is 1,000 kW., during the next 15 minutes is 200 kW. and during the last 10 minutes is 300 kW. Then the

average demand over the period of 30 minutes is:—

$$\frac{(5 \times 1{,}000) + (15 \times 200) + (10 \times 300)}{30}$$

$$= \frac{5{,}000 + 3{,}000 + 3{,}000}{30}$$

$$= \frac{11{,}000}{30} = 367 \text{ kW.}$$

If this were the maximum of these average values over the period, say of three months, which may be the time for which a bill is presented for the energy supplied, the total charge would be 367 $\times$ the charge per kW. of maximum demand plus a charge of so much per unit.

Power Factor and its Bearing on kVA. of Maximum Demand.

It has been assumed in the above that the charge is based on the maximum demand in kilowatts, but this is not always the case. If the power factor of the load in question is low, the current which must be supplied is considerably in excess of that represented by the power in kilowatts supplied, and the supply company must have cables, etc., capable of dealing with this increased current. So that cost of providing the supply is increased. It is for this reason that in many cases the charge is based on kilo-voltamperes of maximum demand, averaged over a definite time interval as explained above.

Either Power Factor or Reactive kVA. should be Measured.

It is advisable, therefore, in such cases, for the consumer to keep his maximum demand under observation and also his power factor. As an alternative to

measuring the power factor, the reactive kVA. or reactive kVA.-hours can be measured.

How the Essential Quantities may be Measured.

If now a consumer wishes to keep his load and his maximum demand under observation, he must have means of measuring the requisite quantities, and the following indicates how this can be done.

Power in Kilowatts.

In many cases it is very useful to know the value of the total load from instant to instant, and for this purpose it is necessary to use a wattmeter, either indicating or recording, connected to the supply at the point where it enters. An indicating instrument enables the total load, taken at any moment, to be read at a glance and can be useful, if attendants are always available, in ensuring that the load does not pass any pre-determined value. On the other hand, it does not give any information as to the manner in which the load is varying unless the readings are logged at short intervals.

Using a Recording Wattmeter.

A continuously recording instrument however, which draws a continuous record of the load on a chart, does give this information and an inspection of the record shows how the load is varying and if it is found to be increasing unduly, steps can be taken to reduce it. By integrating the curve over a definite time interval, say, half an hour, it is possible to determine the average demand in kilowatts over this period.

These continuously recording instruments can be

used for another purpose. Suppose it is discovered that the maximum demand in kilowatts is too high, then it is possible with one of these recording instruments, which will preferably be of the portable type, to determine which particular machine or consuming device is responsible. To do this, the recording wattmeter would be connected to each section of the load in turn, and a record obtained showing how the total load varies over a period of, say, one week. An inspection of the records so obtained will enable the source of the increased load to be detected.

How Reactive kVA. and kVA. are Measured.

Occasionally it is required to obtain a direct indication or record of one or both of these quantities. Reactive kVA. can be measured by the aid of a wattmeter, either indicating or recording, this being connected to the circuit in a special way.

For the measurement of kVA., instruments specially designed for the purpose must be used, and these are available in either the indicating or continuously recording type.

For Kilowatt-hours, obviously a Kilowatt-hour Meter.

The measurement of the energy supplied in kilowatt-hours, is done by integrating meters, as previously described.

How Maximum Demand in Kilowatts is Registered.

Where the charge for energy is based partly on the kW.-hours supplied and partly on the maximum demand in kW., a meter, fitted with a maximum

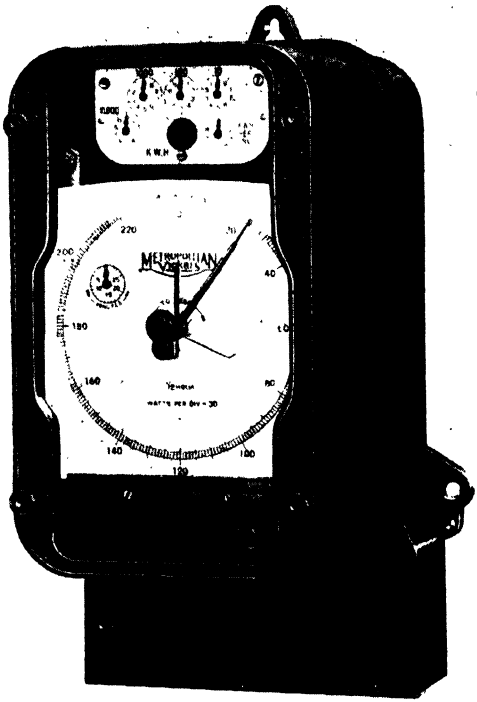


FIG. 28.—WATT-HOUR METER FOR THREE-PHASE, FOUR-WIRE CIRCUIT, FITTED WITH MAXIMUM DEMAND INDICATOR.
(*Metropolitan-Vickers Electrical Co., Ltd.*)

demand indicator, is used. Such a meter is illustrated in Fig. 28.

A meter of this type is fitted with a dial marked in kilowatts in addition to the dials indicating the kW.-hours supplied. The kW. dial gives the maximum demand in kW. in the following manner.

There are two pointers fitted to the dial, one being driven round by the meter. The other is free, but can

be pushed round by the first pointer. At the end of the period during which the demand is averaged the first pointer is returned to the zero position, either by a timing gear contained in the meter or by an external time switch.

Suppose during one period the free pointer is pushed round to a reading of say, 100 kW. It will stay there when the moving pointer is returned to zero. If during the next period the maximum demand averaged over this period does not exceed 100 kW., then the moving pointer will not reach the free pointer, and the latter will be unaffected. If, however, the average demand exceeds 100 kW., the free pointer will be pushed on further, to a value corresponding to this new maximum. In this way the free pointer indicates the maximum value which the demand, averaged over the given period, has attained. After the reading of the maximum demand has been taken, the free pointer can be returned to zero by hand, in readiness for the next reading.

The Construction of the Maximum Demand Meter.

The maximum demand meter consists of a special clock coupled to a standard form of polyphase meter. This clock may be represented schematically by Fig. 29, where the meter rotor drives through a series of gears 1, 2, 3, 4, 7, 8 and 9, to the maximum demand driving pointer. It will be noted that gears 4 and 7 are capable of being de-meshed, since (4) can be taken out of gear by a lever system (5), which is coupled to an electro-magnet (6). During the period, all these gears are in mesh and the maximum demand driving

pointer is driven forward, carrying the demand pointer with it; at the end of the period the electro-magnet (6) is energised by a time-switch, and the maximum demand driving pointer is reset to zero by means of the spiral spring (10); after becoming detached from the actual maximum demand pointer.

At the commencement of the succeeding period, all gears are meshed again, and the maximum demand

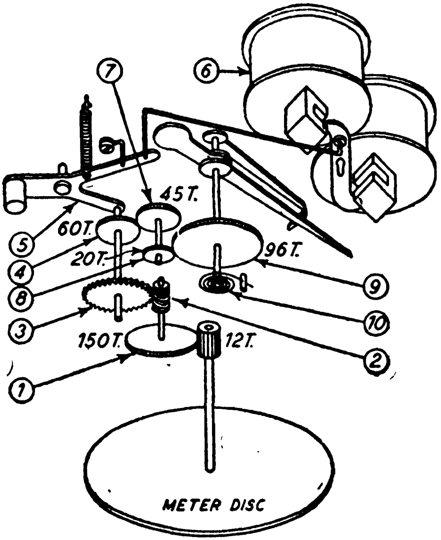


FIG. 29. — MAXIMUM DEMAND INDICATOR MOVEMENT IN PERSPECTIVE.

1 to 4 and 7 to 9, gear wheels; 5, system of levers; 6. electro-magnet; 10, spiral spring.

driving pointer proceeds to drive until the reset period when the operation of resetting is carried out. It will be seen that the maximum demand pointer itself will not be driven forward in succeeding periods unless the units consumed are greater than in the first period, hence the maximum demand pointer itself will establish a reading equivalent to the maximum number of units consumed in any particular period.

Fig. 28 illustrates an example of a combined meter and maximum demand indicator.

The Two Types of Demand Mechanism Compared.

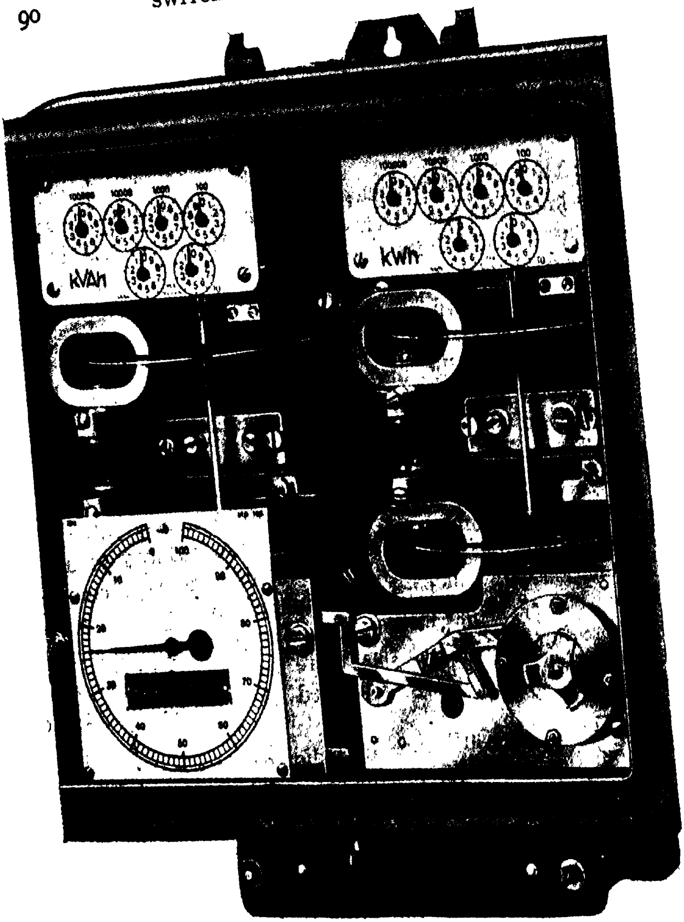
The particular demand mechanism described above is known as the "Held-Off" type, that is to say, the gears are held in mesh by gravity and are demeshed by electrical means. Another type of indicator employs what is known as the "Held-On" type of gear, where the reverse holds. The gears are held in mesh electrically, and are reset by gravity. Both methods have their particular adherents and are widely used.

The main advantage of the "Held-Off" type is the fact that the electro-magnet is intermittently rated, hence losses and consequent wear are reduced to a minimum, but the timing mechanism used in conjunction with this type of maximum demand indicator must be such that in the event of a failure of supply it stops immediately, so that there is no possibility of a double reading being registered on the demand indicator.

The "Held-On" type of indicator does not suffer from this particular disadvantage, but having a constantly energised coil, care has to be taken in the design to reduce losses and wear to a minimum.

The Arrangement of the Time-Switch.

The timing mechanism or time-switch as it is generally termed, which is used with these indicators, generally takes the form of some timing mechanism



FIGS. 30 AND 31.—TWO METERS IN ONE CASE—A kWH METER ON THE RIGHT, AND A kVA METER ON THE LEFT, WITH SYNCHRONOUS MOTOR RESETTING DEVICE.

(*Chamberlain & Hookham Ltd.*)

coupled to a small contactor, and so arranged that the contacts change over at definite periods of time. The timing arrangement itself may consist of an ordinary clockwork motor, driving the contacts through the usual form of escapement or else the switch may be electrically wound again, either using an escapement or a synchronous motor for the timing element itself.

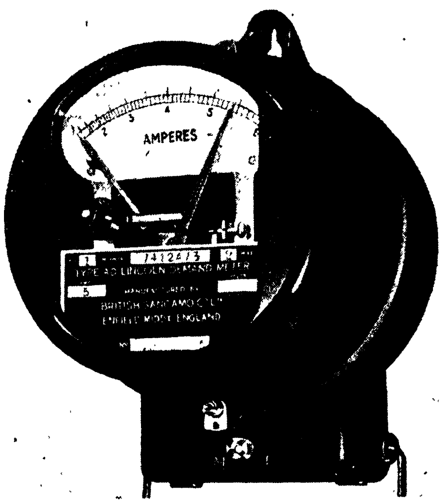


FIG. 32. — SANGAMO TYPE AD THERMAL DEMAND METER.

The meter is suitable for use on either alternating or direct-current circuits, and indicates the maximum demand occurring between times of resetting. Note resetting knob.

Where the voltage of the supply may be assumed to be constant at the declared pressure the meter may also be used as demand kVA. or demand wattmeter and in such instances the dial is scaled, according to requirements.

Another pattern of maximum demand meter is illustrated in Fig. 30. In this type the maximum demand needle is geared to the spindle of the meter rotor through a ratchet mechanism, the ratchet of which is lifted at the end of every 30-min. period. A hairspring on the spindle returns the ratchet shaft to zero every 30 min., and it will be seen that unless the meter makes a greater number of revolutions during some 30-min. period, the ratchet wheel and pointer will

remain at the point previously reached, which corresponds to the maximum demand.

Thermal Type Maximum Demand Meter.

Figs. 33 and 34 show a separate maximum demand thermal type indicator and its interior. This instrument consists of a thermal element with two pointers moving over a graduated scale. Passage of current through the instrument causes one pointer (the demand pointer) to be moved up the scale carrying with it the second or maximum demand pointer. When the current is reduced, the maximum demand pointer is left at the farthest point of its travel, and it remains

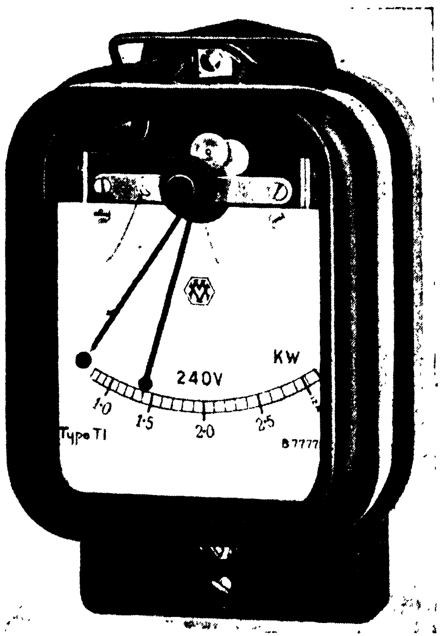


FIG. 33.—SEPARATE MAXIMUM DEMAND INDICATOR.

(*Metropolitan-Vickers Electrical Co., Ltd*).

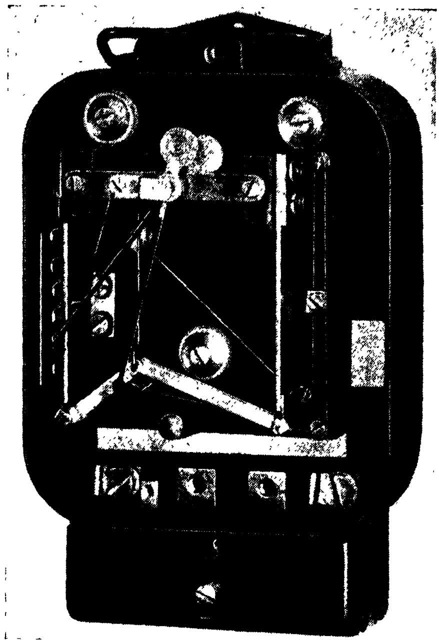


FIG. 34.—INTERIOR OF MAXIMUM DEMAND INDICATOR.

The two bi-metal strips are seen at each side, that on the left being provided with a slipping coil. The lower ends are connected to a linkage gearing up to the pointer.

(*Metropolitan-Vickers Electrical Co., Ltd.*)

there until a greater current at some subsequent time causes it to be farther advanced. It can be returned to the zero position only by means of the resetting knob on the cover which is normally sealed up by the supply authority.

The inside of the instrument is shown in Fig. 34. At each side of the case is a bi-metal strip, that on the left being worked by a heater grid through which the current supply passes. When current is passed through this heater it warms the strip on that side and causes it to curl; the movement of the lower end is transmitted through two links shown to the demand pointer of the indicator. Due to the multiplying action of a

quadrant at the top, a very small amount of curl causes the pointer to travel the full length of the scale. The purpose of the other bi-metal strip without a heater is to provide compensation for local air temperatures.

Refinements to the Maximum Demand Indicator.

Contacts can be fitted to the maximum demand

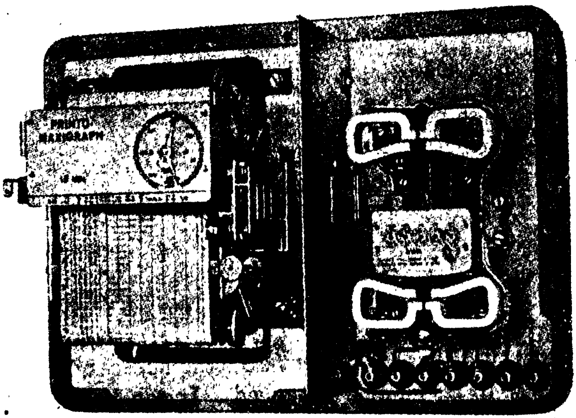


FIG. 35.—COMPLETE MAXIGRAPH WITH COVER REMOVED.
It consists of an electricity meter and a maximum demand recorder housed in a single case.
(Landis & Gyr, Ltd.)

pointer so that an alarm can be given if the maximum demand reaches a predetermined value, and steps can be taken to reduce the demand. This is important in some cases where an economic limit can be placed on the highest value of the maximum demand, and it becomes necessary to sound an alarm when the demand

is approaching this limit. This is further complicated by the time taken to reach the limit.

If, for instance, the period over which the demand is averaged is half an hour, then the alarm sounding at the end of the half-hour period indicates that the limiting value has just been reached, and steps must be taken to see that this value is not exceeded in any subsequent half-hours.

On the other hand, if the alarm sounds within the first ten minutes, say, it will obviously be necessary to reduce the load immediately, as otherwise the maximum value which is permissible may be considerably exceeded, with a correspondingly increased charge for maximum demand.

Arrangements can be made so that a series of alarms can be given depending on the time at which the demand reaches the predetermined value.

Recording the Maximum Demand in Kilowatts.

While meters fitted with maximum demand indicators are quite satisfactory from the point of view of the supply company since they give the maximum demand in kW., and also the units supplied, they are not so satisfactory for the consumer, as it would be very useful for him to know just when this maximum demand occurred and also how it compared with the demand during other periods. It might well be that his load is divided into several sections, as in a large factory, and that each section has its own possible maximum demand. If these maxima all occur at the same time, the resulting maximum demand on the supply will be greater than if they occur at different times. Thus information as to the time the maximum

demand occurred and a comparison with other periods can be very useful.

Such information can be obtained by a maximum demand recorder. In this instrument a pen arm is attached to the driving pointer of the maximum demand indicator and moves a pen across a chart, giving a record of the type shown in Fig. 37. As the driving pointer moves round the dial, the pen is driven across the chart, and is returned to zero with the driving pointer. The maximum value which the pen reaches thus gives the average demand during this period. By this means, a record is obtained of the average demand during successive periods, and an inspection of this record gives the desired information.

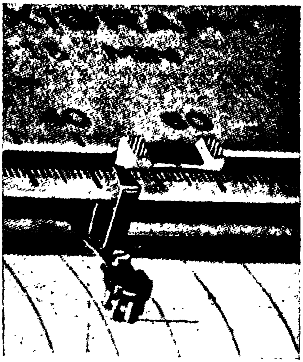


FIG. 36.—RECORDING STYLUS FOR MAXIMUM DEMAND INDICATOR.

(*Landis & Gyr Ltd.*)

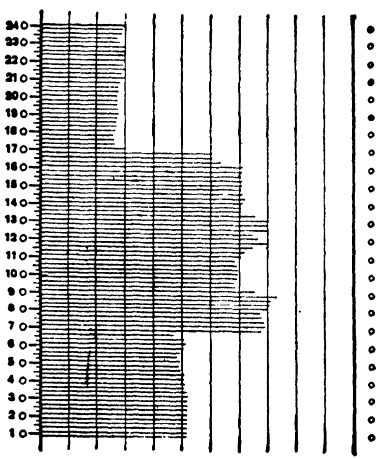


FIG. 37.—REDUCED FACSIMILE OF PORTION OF MAXIGRAPH CHART.

(*Landis & Gyr Ltd.*)

Summation M.D. Metering.

If a works is fed by a number of feeders, it is an easy matter to obtain the total units consumed, by adding up the individual readings on each meter. When, however, the tariff includes a maximum demand charge, this total maximum demand cannot be obtained by adding individual feeder maximum demand indications since there may be a diversity factor between feeders whereby the maximum demands do not occur during the same period. Fig. 38 illustrates the error which may arise due to this diversity factor.

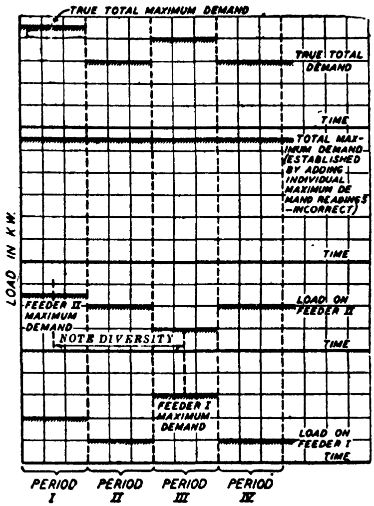


FIG. 38.—THE CORRECT METHOD OF OBTAINING THE TRUE TOTAL MAXIMUM DEMAND OF A NUMBER OF FEEDERS.

It becomes necessary, therefore, to summate all the various feeders on a common meter, driving one maximum demand indicator which will provide the true simultaneous maximum demand. There are two general methods of obtaining this summation, one employing electrical means and the other mechanical means.

Electrical Summation.

When the number of feeders to be summated is

small, three electrical methods provide easy means of summation—(*a*) the paralleling of the current transformers on the meter (Fig. 39), (*b*) the use of summation current transformers (Fig. 40), (*c*) the use of multi-element meters. Each method has its own particular advantages, and hence the actual method adopted for

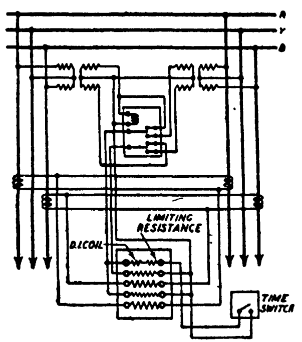


FIG. 39.—DIAGRAM OF CONNECTIONS FOR ELECTRICAL SUMMATION WITH PARALLELED CURRENT TRANSFORMERS.

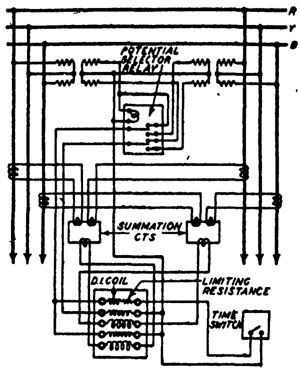


FIG. 40.—DIAGRAM OF CONNECTIONS FOR ELECTRICAL SUMMATION WITH SUMMATION CURRENT TRANSFORMERS.

summating a particular set of feeders must depend upon the local conditions.

Mechanical Summation.

This method, whilst being generally more complicated than the electrical method, can be applied universally, and therefore can be used for any particular summation equipment. Briefly speaking, it consists of installing meters on each feeder, these meters being arranged to transmit electrical impulses (the number being proportional to the energy registered by the

meter) to a mechanical summation meter. This meter converts the electrical impulses into mechanical motion and, by means of differential gearing, adds up all the individual motions to drive a common summation clock together with a maximum demand indicator and, if required, a printer mechanism.

An illustration of the transmitting circuit between feeder meters and a mechanical summator is given in

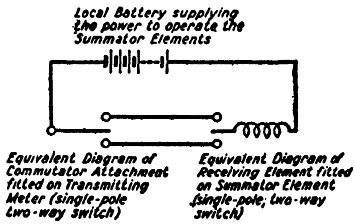


Fig. 41.—The Fundamental Circuit for Transmitting Impulses, Using the Corridor Switching Arrangement.

Fig. 41. It will be noted that this circuit employs the well-known corridor switching arrangement, which has two big advantages, namely, the circuit can always be made at the transmitter end and broken at the receiving end, and secondly, it obviates incorrect transmission due to extraneous vibration.

Measurement of Reactive kVA.

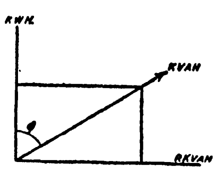


Fig. 42.—Diagram Illustrating kWh, RkVAh and kVAh, and Their Significance One to the Other.

The meters described for the measurement of energy can, with small modifications, be used for other measurements — to wit, reactive kilovolt ampere-hours (RkVAh.), or within certain limits of accuracy kVAh. (see diagram Fig. 42).

If the voltages applied to a

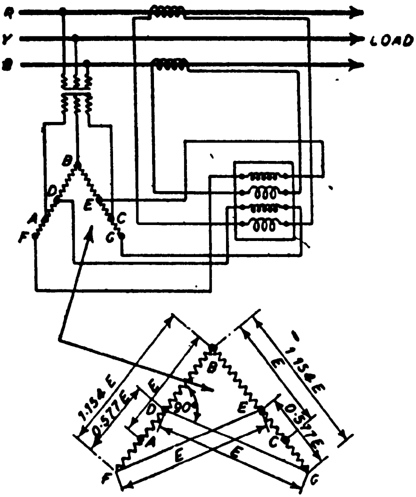


FIG. 43.—DIAGRAM OF CONNECTIONS FOR RkVAh METER, USING A REACTIVATOR.

kWh. meter can be displaced through 90°, then it becomes obvious that such a meter will read RkVAh.

There are several methods of obtaining this displacement, one of the more common types being by the use of what is known as a reactivator. This reactivator is, in effect, a three-phase network with tappings which allows voltages to be taken from it which are displaced from the incoming voltages by the 90°. Fig. 43 illustrates the connections both for the reactivator and the meter whereby the total equipment will measure RkVAh.

Measurement of kVA. Hours.

The measurement of kVA. hours is not so simple or straightforward a matter as the measurement of kW. hours, owing to the fact that while kW. hours have a definite meaning, being the actual energy supplied in any given time, kVA. hours have no such physical meaning. Various special instruments have, however, been designed to measure this quantity.

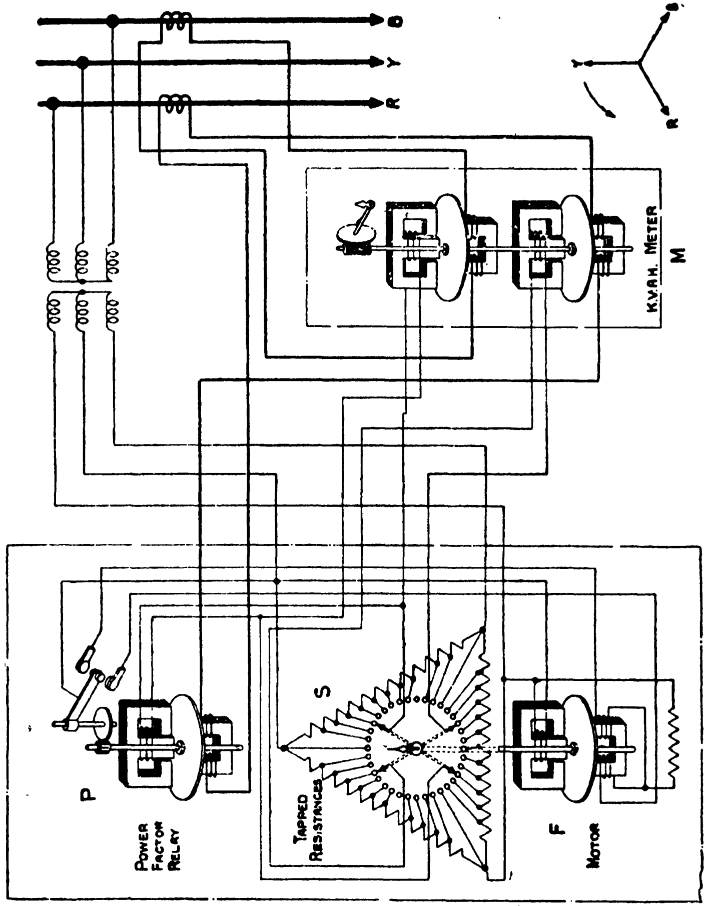


FIG. 44. DIAGRAM OF METRO-VICK EQUIPMENT FOR MEASURING kVAh, COMPRISING A POWER FACTOR COMPENSATING RELAY AND A POLYPHASE WATT-HOUR METER, CONNECTED TO A THREE-PHASE THREE-WIRE CIRCUIT.

(*Metropolitan-Vickers Electrical Co., Ltd.*)

The "Trivector" Instrument.

In some instruments use is made of the relationship which exists between kVA., kW. and reactive kVA. The kW. hours and the reactive kVA. hours are measured and by some special device, usually mechanical in nature, these are combined to give the kVA. hours.

Such an instrument is that known as the "Trivector,"

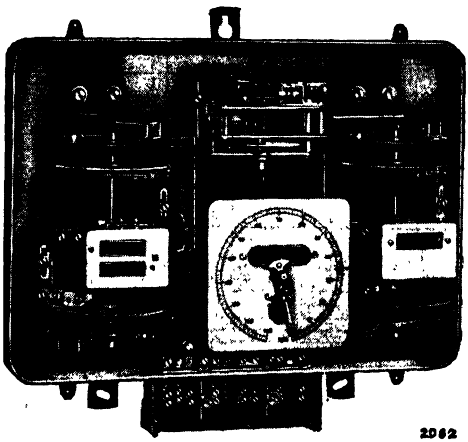


FIG. 45.—TRIVECTOR INSTRUMENT FOR MEASURING kWh, kVAh AND RkVAh.
(*Landis & Gyr, Ltd.*)

and is shown in Fig. 45. The meter measures kW. hours, kVA. hours and reactive kVA. hours. It comprises a kW. hour meter and a reactive kVA. hour meter giving their own readings of these two quantities, and coupled together by a special system of gearing to give the true kVA. hours, irrespective of the power factor. The instrument is normally arranged to be accurate for all lagging power factors from unity to

zero, and an external relay can be used in conjunction with it, to cover the range of leading power factors from unity to zero.

Other instruments are also available using different forms of coupling between the kW.-hour meter and the reactive kVA. hour meter to give the kVA. hours.

A Method of Compensating a kWh. Meter, so that it Registers kVAh.

The measurement of kVAh. normally requires complicated gear if a high degree of accuracy is required, and space will not permit of a description of the various mechanisms available. There is, however, a simple method of compensating a standard kWh. meter so that it will read kVAh. within a reasonable degree of accuracy over a small power factor range. For example, the standard watt-hour meter registers the following product.

Amps. $\times$ volts $\times$ cos ϕ $\times$ hours.

Hence if cos ϕ can be made equal to 1 by compensation, the meter will register kVAh.

A Table Showing Theoretical Errors.

The Table II shows the theoretical errors which can occur for varying phase displacements, and indicates that a total phase displacement of 22° will produce an error of 7.28 per cent. This error can, however, be reduced by speeding up the whole meter curve, whereupon the error over a 22° phase displacement may be plus or minus 3.64 per cent.

If a standard meter is taken, therefore, and the voltage flux is made to lag the voltage by 90° plus 22°, the meter will read kVAh. within errors of plus or minus

TABLE II.

Limits of phase angle.	*Limits of power factor.*	*Maximum theoretical error between kWh. and kVAh.*
Zero to lag or lead of 5°	Unity to lag or lead 0·996	0·38 per cent. slow
" " " 10°	" " " 0·985	1·52 " "
" " " 15°	" " " 0·966	3·41 " "
" " " 20°	" " " 0·940	6·03 " "
" " " 22°	" " " 0·927	7·28 " "

TABLE III.

Angle of lag of current behind potential of circuit.	*Power factor lagging.*	*Theoretical error between kWh. and kVAh.*
0°	1·0	3·6 per cent. slow
6½°	0·99	0·00
22°	0·93	3.6 per cent. fast
37½°	0·79	0·00
44°	0·72	3·6 per cent. slow

3.64 per cent (see Table III) providing the power of the system does not vary outside this 44°. This form of compensation to obtain kVAh. measurements, whilst not producing accurate results, can be of importance on certain circuits, and is, therefore, worthy of mention

It should also be noted that a meter can be compensated for other phase displacements, but the overall theoretical error will always be dependent upon the range of the phase displacement between the voltage and the current.

Maximum Demand in kVA.

Where the tariff in force includes a charge per kVA of maximum demand, this demand must be measured. This can be done in the same way as for kW., by fitting similar maximum demand dials to a kVA.-hour meter. The action of these dials and pointers is exactly the same as already described in connection with the maximum demand in kW.

A Simple Method.

There are, however, other ways in which the maximum demand in kVA. can be indicated. In single-phase or three-phase balanced circuits, where the voltage is reasonably constant, an ammeter fitted with an additional free pointer, similar to those described in connection with the maximum demand dials, can be used. This free pointer is pushed round by the ammeter pointer and indicates the maximum value the current and therefore the kVA. has reached.

This indication, while useful, may be very misleading, as such an instrument will inevitably give the maximum

instantaneous value of the current, and this may be due to a momentary overload, which, as already explained, has no effect on the maximum demand which is averaged over some predetermined period.

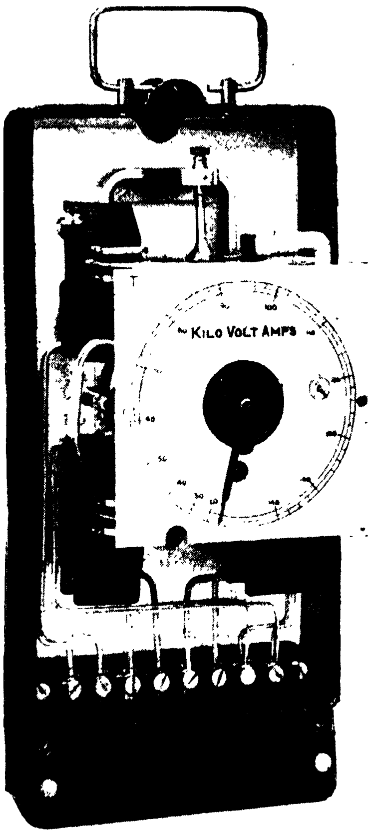


Fig. 46.—Declared Voltage Type of Hill-shotter M.D. Indicator.
(*Aron Electricity Meter Ltd.*)

The Hill - Shotter Maximum Demand Indicator.

To obtain this averaged value, it is necessary to use an integrating instrument as described, or a special kVA. demand indicator such as the "Hill-Shotter" instrument.

If the circuit voltage can be taken as constant, a measurement of the ampere-hours will equally be a measurement of the kVA. hours. The circuit voltage is not usually constant enough for an ampere-hour meter to give the kVA. hours with sufficient accuracy, but if it is fitted with a device which suitably

corrects the readings for any variations in voltage from the normal value, it becomes a true kVA.-hour meter.

And How it Operates.

This is done in the Hill-Shotter instrument which is fundamentally an induction-type ampere-hour meter fitted with a device to compensate for changes in the circuit voltages, usually over a range of $12\frac{1}{2}$ per cent above and below the normal value. The instrument can be made for single-phase and for polyphase, balanced or unbalanced load circuits.

The rotating element drives a pointer round a maximum demand dial in a manner generally similar to that already described, the driving pointer being returned to zero after any predetermined period. The instrument thus gives the maximum demand in kVA., averaged over the period in question.

CHAPTER IV

THE MEASUREMENT OF POWER FACTOR AND FREQUENCY

HAVING discussed the more important measurements of voltage, current, power and energy there still remains a number of special instruments which are frequently used by engineers.

POWER-FACTOR METERS

The phase displacement between voltage and current in A.C. circuits is dependent upon the characteristics of the circuit. A circuit having inductance will cause the current to lag behind the voltage, whilst one having capacitance will cause the current to lead the voltage, the actual angle being a function of the amount of inductance, capacitance and resistance in the circuit. The power-factor of the circuit is the cosine of this angle of displacement (Fig. 1) and is useful information to the engineer in that it tells him what proportion of the current is performing useful work.

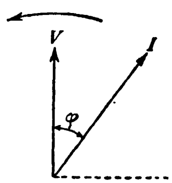


FIG. 1. POWER-FACTOR OF A CIRCUIT.

This measurement can be made with wattmeters, ammeters, and voltmeters $\left(\cos\phi = \frac{\text{watts}}{\text{amps.} \times \text{volts}}\right)$ but it is generally more convenient to use a special

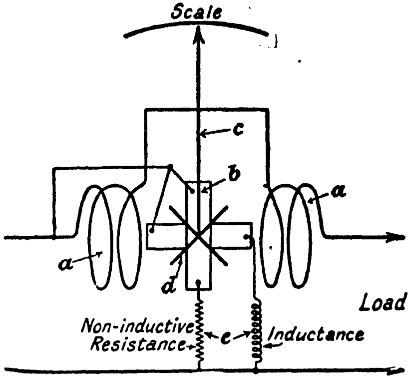


FIG. 2.
THE ESSENTIALS OF A DYNAMOMETER PHASE METER FOR SINGLE-PHASE CIRCUITS.

(*a*) the main current winding; (*b*) the moving element; (*c*) the pointer; (*d*) the damping arrangement; and (*e*) the split-phase device connected to the moving coil.

power-factor meter. These power-factor meters usually operate on either the dynamometer or the moving iron principle.

The Dynamometer Type.

Dealing with the single-phase type this may be represented schematically by Fig. 2. The fixed coils (*a*) carry the load current or its equivalent, whilst the moving coils (*b*) displaced one from the other by 90° are connected through a network generally known as a phase-splitting device (*e*), across the voltage of the supply. This phase-splitting device consists of a resistance connected in series with one of the coils and a

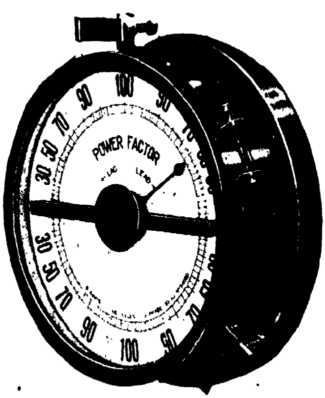


FIG. 3.—POWER-FACTOR METER, ROUND FLUSH PATTERN.

condenser or reactor connected in series with the other coil. The two currents flowing in the moving coils will therefore, be displaced one from the other by approximately 90°, which will, in effect, produce a rotating magnetic field. The currents are led into and out of these coils by means of ligaments which are so weak that the control torque they produce is negligible. The pointer (c) is connected solidly to these moving coils and registers on a scale.

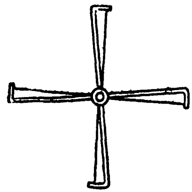


FIG. 4. VANES CONNECTED TO THE POINTER SHAFT TO PROVIDE PNEUMATIC DAMPING.

The driving torque of such an instrument depends upon the interaction of the fluxes emanating from both the fixed and moving coils and is dependent upon the phase displacement between the current and voltage of the system.

The damping is effected either pneumatically (Fig. 4 illustrates a set of vanes in place of the usual piston and cylinder; this form is required because the moving element must be capable of a 360° movement), or electromagnetically by means of the usual disc and permanent magnet.

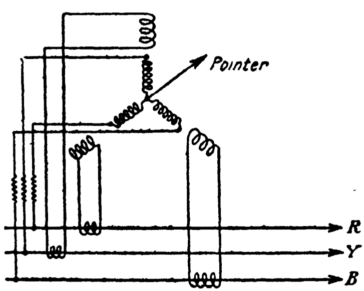


FIG. 5.—CONNECTIONS OF A THREE-PHASE DYNAMOMETER POWER-FACTOR METER.

A power-factor indicator for use on a polyphase circuit is generally similar in construction to that already described,

except that the phase-splitting device is omitted and the angular displacement of the phases themselves is used to obtain the necessary rotating magnetic field. Fig. 5 illustrates the connections of a three-phase power-factor meter for use on unbalanced loads.

Characteristics of the Dynamometer Type.

The single-phase type is liable to errors due to frequency, and wave-form variations, because of the phase-splitting network. These errors are, however, reduced by means of compensation to limits which are negligible for ordinary commercial measurements.

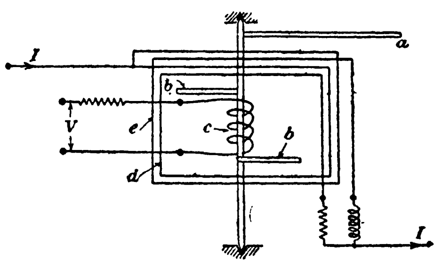


FIG. 6. — SCHEMATIC DIAGRAM OF A SINGLE-PHASE MOVING IRON POWER-FACTOR METER.

(*a*) pointer; (*b*) moving iron; (*c*) polarising winding; (*d*) and (*e*) distributed windings.

In the case of the polyphase type, the errors can be entirely eliminated, due to the absence of this network.

Another point which should be observed in connection with power-factor meters, is the question of the load current flowing through the meter. Whilst the instrument is practically independent of voltage and current variations the current should not be allowed to drop below 20 per cent. of the rated value of instrument, otherwise errors may be introduced due to friction.

The Moving Iron Type.

A single-phase instrument of this type is illustrated schematically in Fig. 6. The pointer is coupled to the moving irons, which are specially shaped and displaced 180° one from the other. These irons are embraced by a polarising winding, which is connected across the voltage. Two other coils, each consisting of distributed windings, are arranged to surround

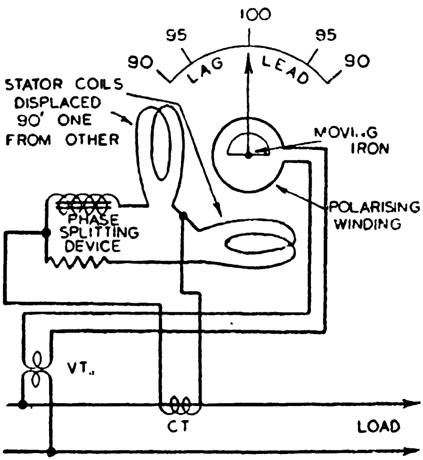


FIG. 7. SINGLE-PHASE, MOVING IRON POWER-FACTOR METER SHOWN SCHEMATICALLY, OPERATED THROUGH CURRENT AND VOLTAGE TRANSFORMERS

the moving irons and polarising winding and to be displaced one from the other by 90°. The coils are connected to a phase-splitting network and carry the main current or its equivalent.

The principle of operation is similar to that of the dynamometer type, the torque being proportional to the phase displacement between the voltage and current of the system.

The damping arrangements are similar to those used on the dynamometer type.

Connections of Polyphase P.F. Meters.

The polyphase form has three distributed coils in place of the two already described in the single-phase type, and here again the phase-splitting device is obviated, since the requisite rotating field is produced by the angular displacement of the three-phase supply. Fig. 8 illustrates the connections for a polyphase instrument and it should be noted that since there is only one voltage winding, the instrument can only be truly accurate under balanced voltage conditions. Actually this limitation is not serious in practice, since the indication is accurate to within the usual commercial limits with voltage unbalance up to 10 per cent., which is rarely exceeded in practice.

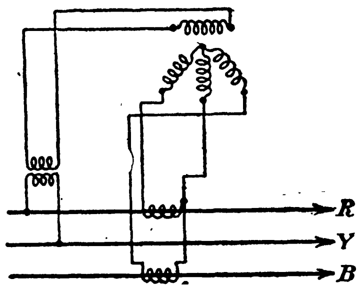


FIG. 8.—CONNECTIONS OF A MOVING IRON THREE-PHASE POWER-FACTOR METER.

Characteristics of the Moving Iron Type.

The single-phase instrument has similar errors to those already mentioned in connection with the dynamometer type and even in the case of the polyphase instrument it is not possible to eliminate the errors entirely.

In spite of these errors, however, the type is capable of producing a high degree of accuracy for ordinary commercial purposes. Furthermore, the absence of ligaments and the like ensures a very robust instrument which is very suitable for switchboard work.

SYNCHROSCOPES

A modified form of power-factor meter can be used to establish synchronism between two machines or a machine and the busbars. This consists of a single-phase power-factor meter with both sets of windings arranged for connection across voltage supplies, one supply being the busbars and the second being the machine which is being regulated prior to being synchronised.

The common forms of connections, used for a complete synchronising equipment, comprising lamps, voltmeters and synchroscope are dealt with in Chapter V.

PHASE ROTATION INDICATORS

During the connection of electrical apparatus to polyphase systems, it is often necessary to establish the correct phase rotation of the system. This phase rotation can, if necessary, be checked by means of choke coils, lamps and resistances or polyphase wattmeters, but the simplest method is to use a phase rotation indicator.

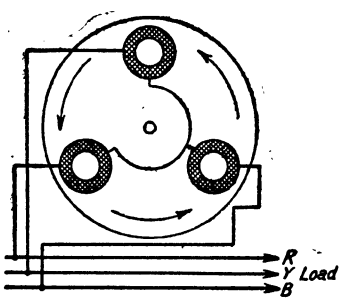


FIG. 9.—PRINCIPLE OF THE PHASE ROTATION INDICATOR.

When the phases of the supply are connected to the colour terminals of the instrument, the phase sequence of the supply is indicated by the rotation of the disc.

This indicator is represented schematically in Fig. 9 and consists of three small electromagnets, and an aluminium disc suspended in jewelled bearings.

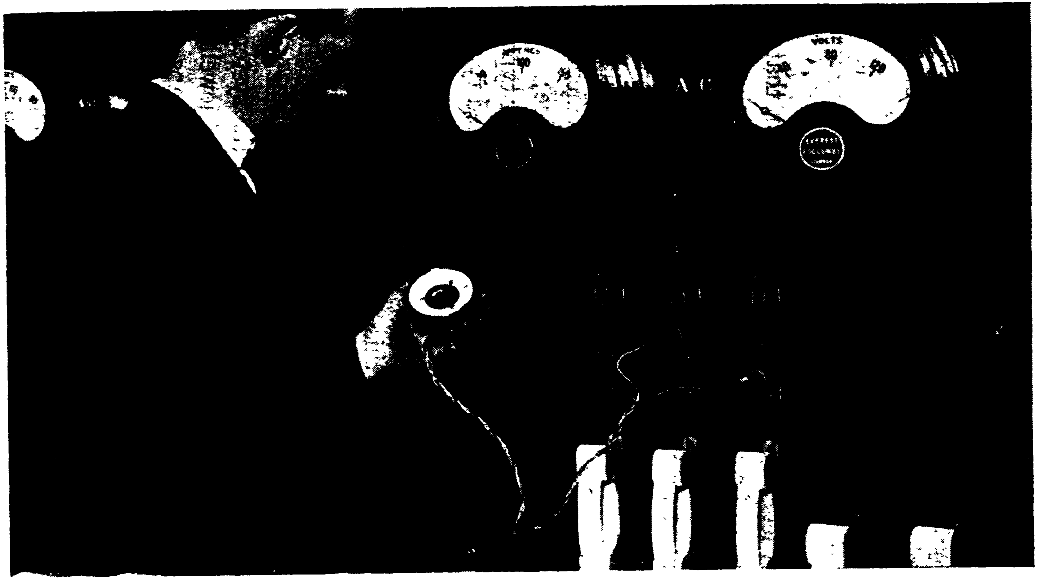


FIG. 10.—DETERMINING THE ORDER OF PHASE SEQUENCE BY MEANS OF A PHASE ROTATION INDICATOR.

The clips may be attached to any convenient terminals, as shown above, and the disc then indicates by the direction of its rotation in which order the voltages are reaching their maximum at these three terminals.

(*Everett, Edgcumbe & Co., Ltd.*)

When the three coils are energised from a polyphase supply, a rotating magnetic field is generated, the rotation of which is dependent upon the phase rotation of the system. The disc rotates either clockwise or counter clockwise and thus indicates the phase rotation of the system.

FREQUENCY METERS

A knowledge of the frequency of the system, that is, the number of complete cycles of oscillation per second (Fig. 11) is necessary if the system is to work in synchronism with other supplies.

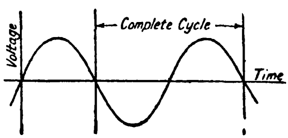


FIG. 11.—ILLUSTRATION OF FREQUENCY.

Three types of instruments are in general use to make this measurement:—

(1) Induction type;
(2) Dynamometer type;
(3) Vibrating reed type.

The Induction Type.

In its simplest form this type can be represented schematically by Fig. 12 and consists of two electro-magnets (*a*) each complete with a shading loop (similar to that used in induction ammeters and voltmeters) which are connected across the voltage of the system. A specially shaped disc (*b*) suspended on jewelled bearings is arranged to swing in the air gaps of these two electro-magnets. The coil (a_2) is connected in series with a reactor and the coil (a_1) connected in series with a resistance. It will be seen that the current flowing through the coil (a_1) is practically independent of frequency whilst that flowing through the coil (a_2) is dependent upon the frequency, hence the torque of the

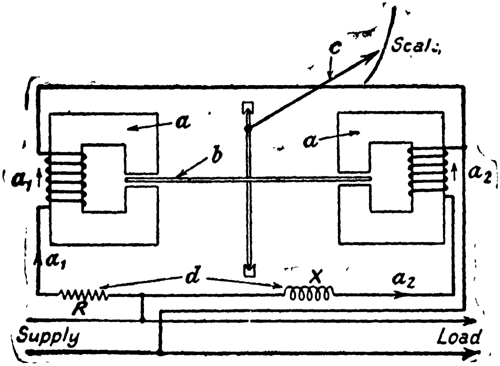


FIG. 12.—THE INDUCTION TYPE OF FREQUENCY METER.
Key to lettering: (*a*) two electro-magnets; (*b*) specially shaped disc; (*c*) pointer; (*d*) split-phase device.

instrument which is a differential of the two torques will be a function of the frequency of the supply.

The control torque of this type of instrument is provided by means of gravity.

Characteristics of the Induction Type.

In common with induction ammeters and voltmeters the instrument is subject to errors due to voltage, temperature and wave-form variations and also suffers from a cramped scale. In spite of these disadvantages, however, the instrument is largely used commercially, since with suitable design, the type can be made into a very robust form of instrument, which is capable of a high degree of accuracy.

A modification of this type, incorporating both reactors and condensers, provides what is known as the resonance type of induction frequency meter, whereby a long scale reading is obtained for a small frequency change.

The Dynamometer Type.

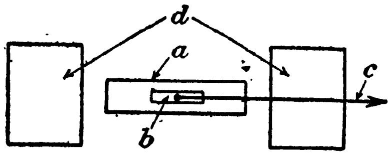


FIG. 13.—SCHEMATIC DIAGRAM OF DYNAMOMETER-TYPE FREQUENCY METER.

Fig. 13 illustrates schematically the dynamometer type of frequency meter. It consists of a moving coil (*a*) and polarising iron (*b*) coupled to a pointer (*c*). This moving system is mounted on jewelled bearings inside the fixed coils (*d*). The whole is connected in bridge fashion with suitable resistances and reactors across the voltage of the supply (Fig. 14).

The driving torque is due to interaction of the two coils, the polarising iron being used for location purposes when no current is flowing through the moving coil.

The control torque is provided by gravity.

The instrument suffers from the same errors which are inherent in the induction type, but notwithstanding these, it is capable of a high degree of accuracy.

The main advantage of this type over the induction pattern is the fact that it can be assembled in a smaller compass than the former.

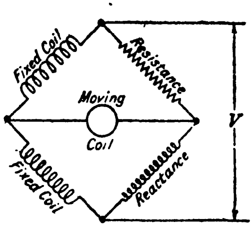


FIG. 14.—DIAGRAM OF CONNECTIONS FOR DYNAMOMETER-TYPE FREQUENCY METER.

The Vibrating Reed Type.

This type was originally suggested by Professor Ayrton, who demonstrated that if a number of magnetic reeds of different lengths were located near an electro-magnet, and energised from a source of alternating current, then only

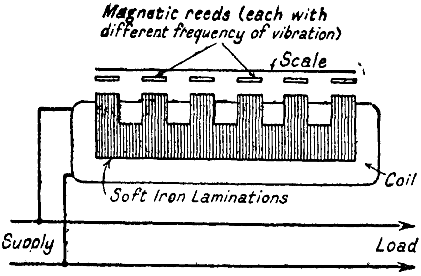


FIG. 15.—THE RESONANT REED TYPE OF FREQUENCY METER.

This consists of an electro-magnet and a number of vibrant reeds. When the instrument is energised only those reeds with a corresponding frequency will vibrate and so furnish the required indication.

those whose free natural period of vibration was half the frequency of the supply, would vibrate, leaving the remaining ones stationary.

Fig. 15 illustrates schematically such an instrument, showing the electro-magnet, which is energised from a source, the frequency of which is to be measured, and

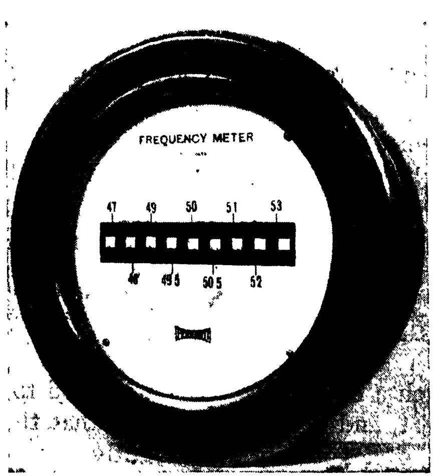


FIG. 16.—FREQUENCY METER OF THE RESONANT REED TYPE.

the various reeds, the natural frequency of vibration of each, differing slightly from that of its neighbour.

Characteristics of the Vibrating Reed Type.

This type is rather more difficult to manufacture and calibrate than those already described, since each reed needs careful adjustment to obtain the correct frequency of vibration. Once, however, the adjustment has been carried out, the result is an instrument which is robust and capable of a good degree of accuracy over a considerable voltage range.

The limitation of the type is the question of selecting reeds with sufficiently small intervals between them so that accurate readings are obtainable.

In practice it is usual to limit this interval to 1/4 cycles, hence the accuracy of scale reading is not so great as with the types already described.

Reading a Vibrating Reed Frequency Meter.

Vibrating reed instruments are not altogether easy to read, since the frequency may lie between the values to which two neighbouring reeds are tuned. Fig. 17

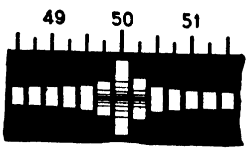


FIG. 17.—PART OF THE SCALE OF A VIBRATING REED FREQUENCY METER.

The value of the frequency may be estimated from the relative amplitude of the swing of the reeds as 50.1 cycles per second.

shows such a case. The reeds are tuned to a quarter cycle apart, and it will be observed that the one next above 50 cycles is vibrating slightly more than that below 50 cycles, so that the frequency may be read as about 50.1 cycles per second.

Speed Indicators.

Another type of instrument which is sometimes used as a measure of frequency is the speed indicator.

Knowing the number of poles of the alternator the frequency can be obtained from the formula:

Frequency $= np$.

where n = revs. per sec. of alternator.

p = pairs of poles.

Hence an indicator arranged to measure the speed of the alternator can if required be scaled to register frequency.

One type sometimes used for this purpose consists of a small D.C. permanent magnet generator coupled to the alternator. The voltage obtained from this generator (being proportional to the speed) is measured by a moving coil instrument which can, therefore, be scaled either in revolutions per minute or in frequency.

CHAPTER V

SYNCHRONISING INSTRUMENTS

THE fundamental principles of synchronising have changed very little since the early days when attempts were first made to run alternators in parallel. The methods of applying these principles have, however, changed out of all recognition, and, as switching schemes have grown both in size and complexity, more elaborate apparatus and connections have been found necessary in order that the actual synchronising operations might be rendered as simple as possible and to reduce to a minimum the possibility of human error. Many systems have been evolved with this end in view, and it is proposed to discuss a few typical examples to illustrate the factors to be considered in the choice of a suitable scheme.

Synchronising Lamps.

Whenever two sources of supply are to be connected together three conditions must be fulfilled as follows:—

(1) The speed of the incoming machine must be adjusted until its frequency is equal to that of the supply to which it is to be connected.

(2) The voltage of the incoming machine must correspond with that of the supply to which it is to be connected.

(3) The incoming machine must be switched in when the two supplies are in phase.

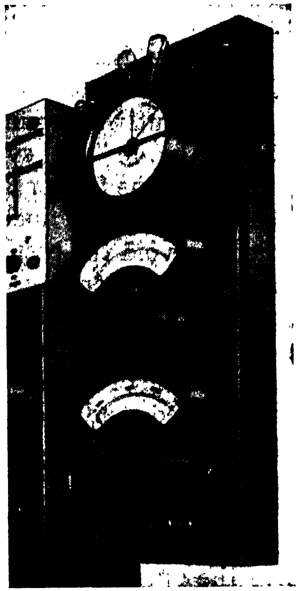


FIG. 1.—SYNCHRONISING BRACKET MOUNTED ON A CONTROL BOARD.

In the early days the types of machine in use were such that very great accuracy in judging the moment for synchronising was of little importance and a "bad shot" did not have a very serious effect on the system. Consequently, it was found that sufficiently accurate indication was obtained by the simple expedient of connecting ordinary lamps across the terminals of the paralleling switch. Even to-day synchronising lamps are incorporated in most synchronising equipments, although their purpose is now limited to providing a rough indication for preliminary adjustments until the difference in the speeds of the two machines is brought to a value which is readable on the more sensitive synchroscope.

It will be of interest to trace the development of the original lamp schemes, as these form the basis of all subsequent schemes, the principles of which may be followed more readily by considering these simple methods.

Indication of Synchronism. "Lamps Bright" *v.* "Lamps Dark".

The lamps may be connected in either of two ways, according to whether they are to attain maximum

brilliance at the moment of synchronism or whether synchronism is indicated when the lamps cease to be illuminated. There is something to be said for both schemes, but the arguments are strongly in favour of "lamps bright" at synchronism as against "lamps dark," and the former is now almost universal practice. The "lamps dark" method is sometimes employed in order to avoid the cost of a reversing transformer, but this is false economy, as it suffers from two serious drawbacks. In the first place, it is extremely difficult to judge the exact moment of synchronism, as there is a wide range of voltage over which no illumination can be observed, and the lamp appears to be quite dark. This condition may occur at about 30 per cent. of normal voltage, at which value the difference in phase angle between the two machines would be considerable. The second objection is that a burnt out lamp would give the operator a false indication of synchronism.

Application of Lamps to Low Voltage Systems.

Various methods of applying direct connected lamps to low voltage systems are shown in Figs. 2 (*a–e*), and when the principles of these are understood, the application to high voltage systems, employing voltage transformers, can be developed quite simply.

Isolated Neutrals. Lamps Dark.

When the two supplies are insulated from one another, as in Fig. 2*a*, two sets of lamps are required in order to provide a complete circuit through two phases of both machines. It will be obvious that one set of lamps alone would not provide a complete circuit.

Each lamp is connected between similar phases, so

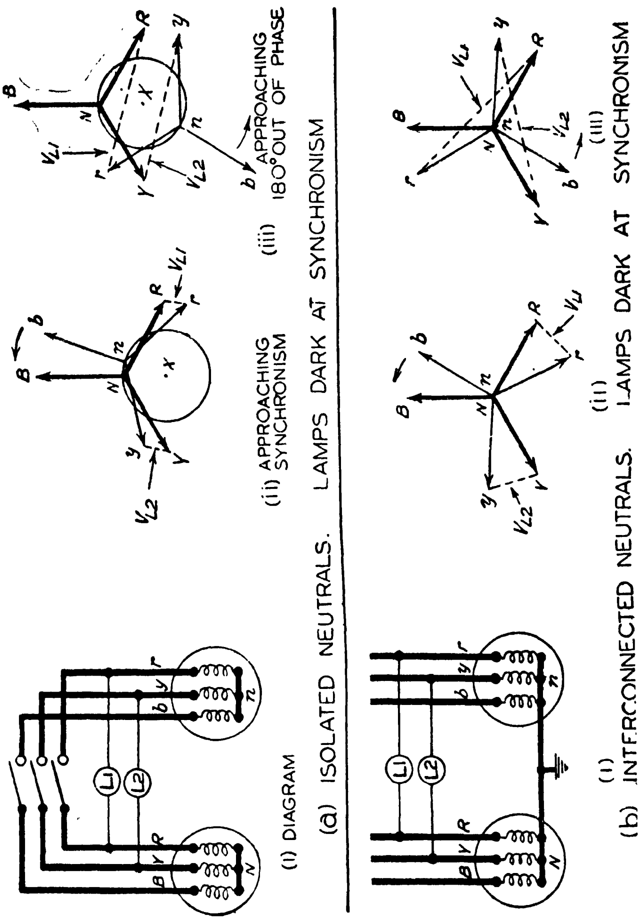


FIG. 2. METHODS OF SYNCHRONISING WITH LAMPS ON LOW VOLTAGE SYSTEMS.

that when the two machines are generating equal voltages and are in phase with one another there is no voltage across the lamp.

The variations in the lamp voltages will be clear from the vector diagrams, which show the conditions as synchronism is approached and also when approaching 180° out of phase.

For convenience, it is assumed that the system, RYBN, is stationary, and that the system, *rybn*, is rotating relative to the first in an anti-clockwise direction. As the only connection between the two systems is that formed by the lamp circuit, the equipotential point of this circuit must lie mid-way between the lamp voltage vectors, V_{L1} and V_{L2}, and the whole system rotates round an artificial neutral point, X.

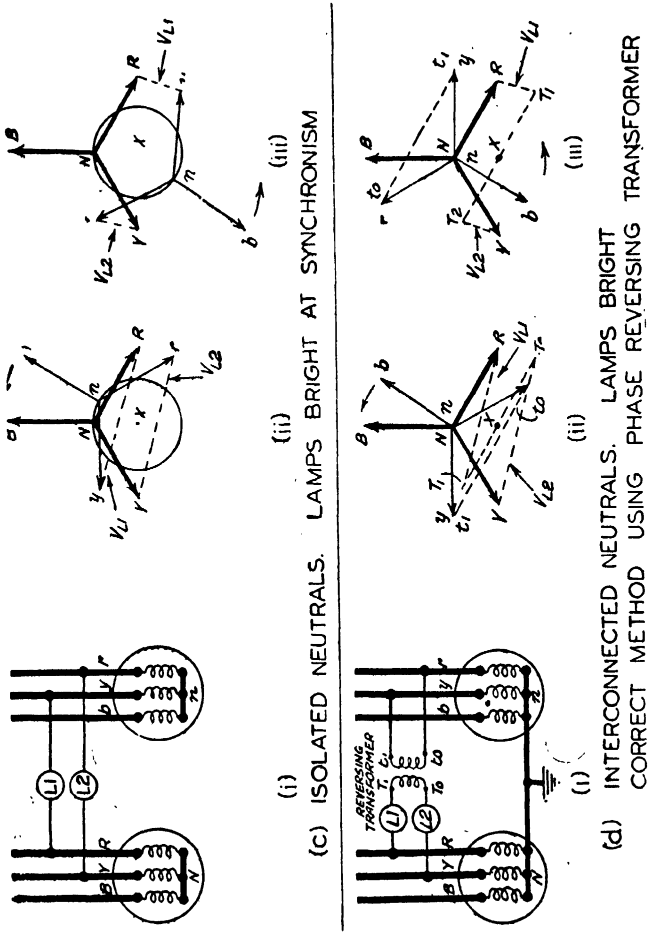
It will be seen that the lamp voltages V_{L1} and V_{L2} vary from zero at synchronism, to a maximum value equal to the phase to phase voltage when the machines are 180° out of phase.

Interconnected Neutrals. Lamps Dark.

The moving system in this case (Fig. 2*b*) rotates round the fixed neutral point N, and the lamp voltage varies from zero at synchronsim, to a maximum value equal to twice the phase to neutral voltage when the two machines are 180° out of phase.

Isolated Neutrals. Lamps Bright.

Two sets of lamps are required in this case (Fig. 2*c*), each connected across opposite phases, and the lamp voltages vary from a maximum value equal to the phase to phase voltage at synchronism to zero when the machines are 180° out of phase.



(c) ISOLATED NEUTRALS. LAMPS BRIGHT AT SYNCHRONISM

(d) INTERCONNECTED NEUTRALS. LAMPS BRIGHT CORRECT METHOD USING PHASE REVERSING TRANSFORMER

FIG. 2. METHODS OF SYNCHRONISING WITH LAMPS ON LOW VOLTAGE SYSTEMS.

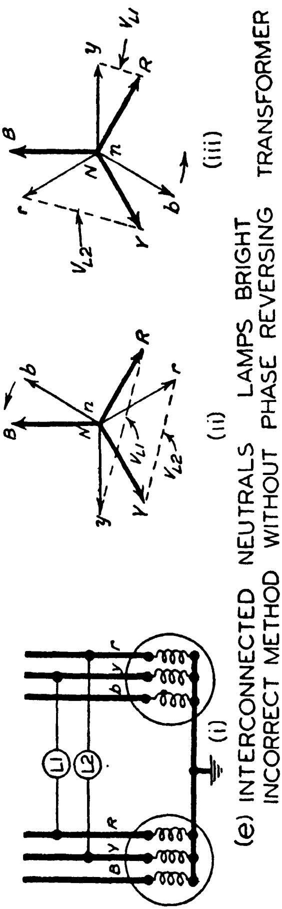


FIG. 2. METHODS OF SYNCHRONISING WITH LAMPS ON LOW VOLTAGE SYSTEMS.

Interconnected Neutrals. Lamps Bright.

For these conditions it is necessary to introduce a phase reversing transformer having a ratio of 1/1 (Fig. 2*d*). The transformer primary and lamp voltage vectors, T_0 T_1, V_{L1} and V_{L2}, rotate round the equipotential point X, and it will be seen that the lamp voltages are equal to one another and vary from a maximum value equal to phase to phase voltage at synchronism to zero when the machines are 180° out of step.

Reason for Phase Reversing Transformers.

The reason for introducing the reversing transformer for the conditions under (*d*) will be appreciated after a study of Fig 2*e*, which shows a scheme in which the lamps are direct connected between opposite phases of the two machines.

The lamp voltage V_{L1} at synchronism is equal to the

phase to phase voltage, but this is not the maximum voltage which occurs when the machines are 60° out of phase, and is equal to twice the phase to neutral voltage. Zero voltage on the lamp occurs when the machines are only 120° out of phase, whilst at 180° out of phase there is a voltage across the lamp equal to phase to neutral voltage.

The voltage variations are equally bright only at synchronism, but they are not then at maximum brilliance.

The direct connected lamps bright is, therefore, unsuitable for systems in which the neutrals are interconnected. For these conditions it is necessary to isolate the synchronising connections by means of a reversing transformer or by employing ordinary voltage transformers for each supply.

Voltage Transformers.

When using voltage transformers, it is necessary to cross-connect them in order to obtain maximum voltage at synchronism. If, however, all the transformers have the same phase earthed, a phase-reversing transformer is required.

Voltage transformers are necessary on all systems exceeding 650 volts between phases, but even on lower voltage systems they are desirable in order to limit the voltage which may appear across the synchronising instruments and also on account of the simplification of instrument wiring and the reduction in the number of plugs and sockets which follow.

Synchroscopes.

Various forms of synchroscopes are available, but

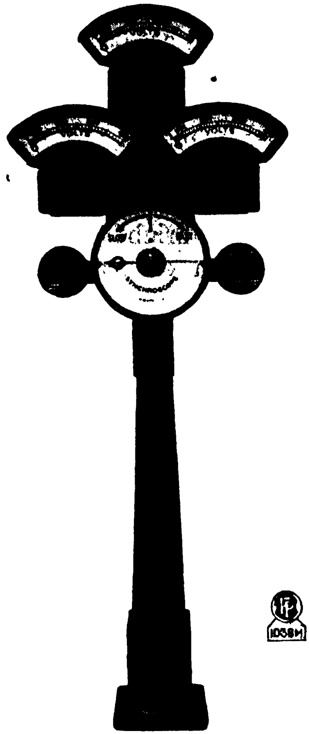


FIG. 3.—INSTRUMENT PEDESTAL EQUIPPED WITH SYNCHROSCOPE, VOLTMETERS AND FREQUENCY INDICATOR.
(*Ferguson, Pailin, Ltd.*)

they all have one common feature in that the moving system is coupled to a rotating pointer, the speed of which is a function of the difference between the speeds of the two machines and the direction of rotation indicates whether the incoming machine is fast or slow, relative to the running machine. The position of the pointer at any instant is also a measure of the phase difference at that instant, the twelve o'clock position representing synchronism between the two machines.

Voltmeters.

In addition to the synchroscope, two voltmeters are required, one for the incoming and one for the running supplies. They should be provided with large scales so as to be easily read from a distance, and, for the same reason "set up" scales are desirable in order to allow closer regulation of the voltage.

Frequency Meters.

Whilst not so essential for synchronising purposes,

frequency indicators are of value in furnishing an indication of the actual speeds of the machines, whereas the synchroscope simply provides an indication of the difference in speeds. They may be of the vibrating reed or of the pointer type (see Chapter IV).

Choice of Synchronising Schemes.

Having discussed the broad principles of synchronising, we will now consider their application to typical schemes.

Many systems have been evolved of varying complexity, according to the system and operating conditions to be met, and the main considerations affecting the choice are summarised below.

Lay-out of Switching Scheme.

In most synchronising schemes the synchronising connections are arranged to mimic the main conductors, and the schemes are, therefore, intimately bound up with the system lay-out and method of control as follows:—

(*a*) Number and type of circuits, e.g., generators, incoming feeders, busbar couplers, bus section switches, reactor switches, etc.

(*b*) Type of busbar system, e.g., whether single bus, duplicate bus or ring busbars.

(*c*) Method of busbar selection, e.g., whether by means of selector switches, transfer breakers, or duplicate oil circuit-breakers.

(*d*) Method of control, e.g., whether by hand or electrical means.

Safeguards Against Errors.

The scheme to be adopted will also depend on the extent to which the operator is to be prevented from making mistakes, such as synchronising against one point of the system whilst the paralleling connection is made at another point, or switching in an incoming supply without carrying out the necessary synchronising operations. According to the complexity of the system and the degree of skill possessed by the operating staff, the scheme may be:—

(*a*) Hand operated non-interlocked.
(*b*) Hand operated interlocked.
(*c*) Semi-automatic.
(*d*) Fully automatic.

In large undertakings, mistakes in synchronising may have very disastrous consequences, and, in an endeavour to reduce the possibility of such mistakes to a minimum, more and more safeguards are being called for in synchronising schemes. On the other hand, it must not be overlooked that additional connections and apparatus introduce more potential sources of trouble, and if defects should arise on such schemes, difficulty may be experienced in getting a large machine on load at a time when delay might be a serious matter.

The methods of interlocking should, therefore, be kept as simple as possible, reliance being placed on operators having the requisite degree of skill and the interlocks regarded simply as additional safeguards against occasional lapses which might occur under emergency conditions.

Single Busbar Low-voltage System.

Fig. 4 shows a simple, straightforward scheme

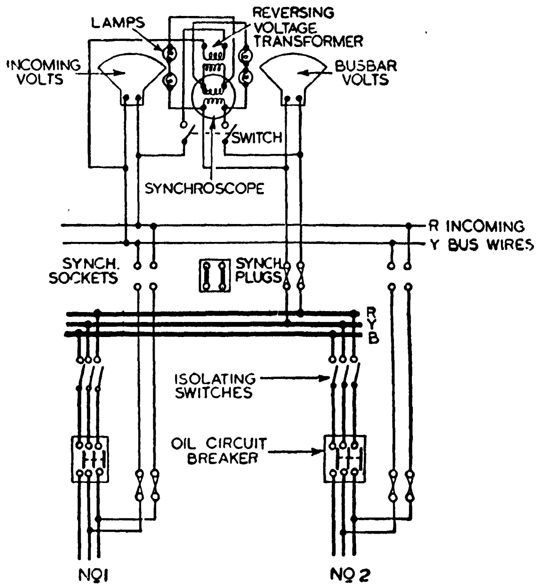


FIG. 4.—CONNECTIONS FOR SYNCHRONISING WITH "LAMPS BRIGHT" ON SINGLE BUS BAR LOW-VOLTAGE SWITCHGEAR.

incorporating one set of synchronising wires extending over all machine or incoming feeder panels, and which may be energised from any of the incoming supplies by inserting the portable plug in the appropriate sockets. When an incoming supply is to be synchronised, the plug is inserted in the sockets connected to that supply. The running and incoming operating windings of the synchroscope are then connected to the busbars and incoming supply wires respectively by means of the double-pole switch. A reversing transformer is included in this scheme in order to obtain lamps bright at synchronism, the total rating of the lamps being

equal to twice the phase to phase voltage of the system.

The voltmeters may be left permanently connected as shown, in which case the incoming voltmeter will read the voltage of any of the incoming supplies according to the position of the plug.

Double Busbar Low-voltage System.

The previous scheme is extended in Fig. 5 to a double

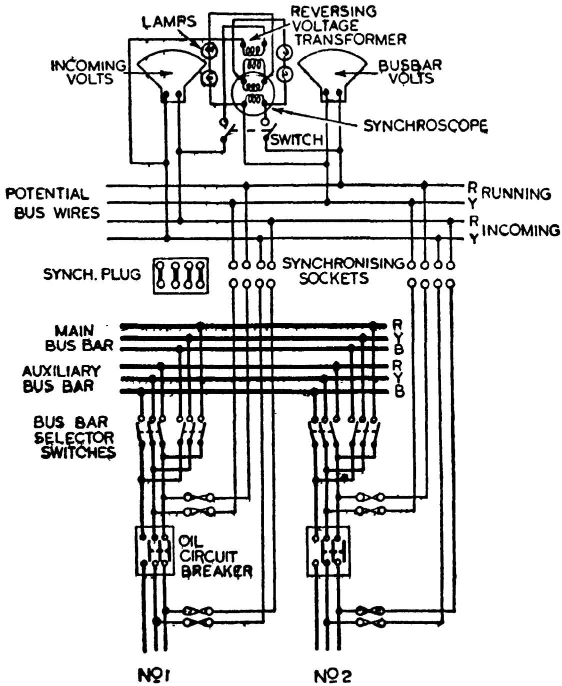


FIG. 5.—CONNECTIONS FOR SYNCHRONISING WITH "LAMPS BRIGHT" ON DUPLICATE BUS BAR LOW-VOLTAGE SWITCHGEAR.

busbar system employing selector switches, but, despite its simplicity, it is an interlocked scheme in that it is not possible for an operator to synchronise against the wrong set of busbars.

Two sets of bus wires are necessary, one set of which is connected to the busbar side and one set to the supply side of any breaker by the insertion of one plug only in the appropriate sockets.

Unfortunately such a simple scheme is impracticable on high voltage systems, firstly on account of the large number of voltage transformers which would be required, and secondly on account of objections to voltage transformers connected to the busbar side of switching equipments.

Single Busbar Scheme with Busbar P.T.

This is the most simple scheme for high voltage systems where potential transformers must be employed; one synchronising plug only is required, which is inserted in the sockets on the panel controlling the machine which is to be synchronised (Fig. 6).

This energises the incoming bus wire, and also the corresponding winding of the synchroscope, from the machine potential transformer. At the same time it also connects the busbar winding of the synchroscope to the running bus wire, which is permanently connected to the busbar potential transformer.

The synchroscope can be completely isolated by means of the plug, and a separate disconnecting switch is, therefore, unnecessary.

The phase terminal of the busbar potential transformer which is chosen for connecting to the common earth wire is of opposite polarity to that which is

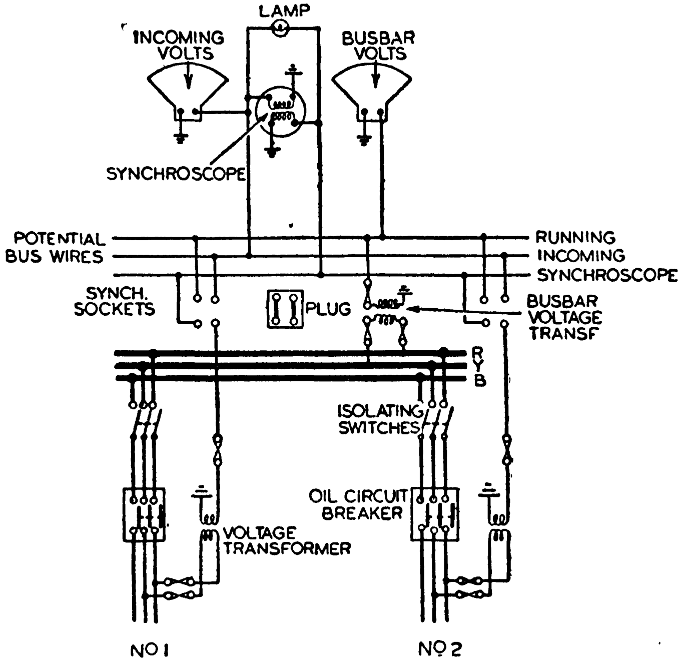


FIG. 6.—CONNECTIONS FOR SYNCHRONISING WITH "LAMP BRIGHT" ON SINGLE BUS BAR HIGH-VOLTAGE SWITCHGEAR.

earthed on the machine potential transformers. In this way lamps bright at synchronism may be obtained without introducing a phase reversing transformer.

In order to simplify the connection diagrams where voltage transformers are incorporated, individual "earths" have been shown at various points, but it is important to note that each of these individual points must be connected to a common earth wire (not shown in the diagrams). It is not sufficient to rely upon the conductivity of the metal supporting structure.

Single Busbar Scheme. Machine P.T.'s only.

On important installations it is not considered good practice to employ potential transformers connected to the busbars, as a potential transformer failure which is not properly cleared by its protecting fuses may lead to a total shut down of the section to which it is connected.

In Fig. 7, therefore, we have shown the more usual arrangement utilising voltage transformers connected to the incoming sides of the breakers for energising

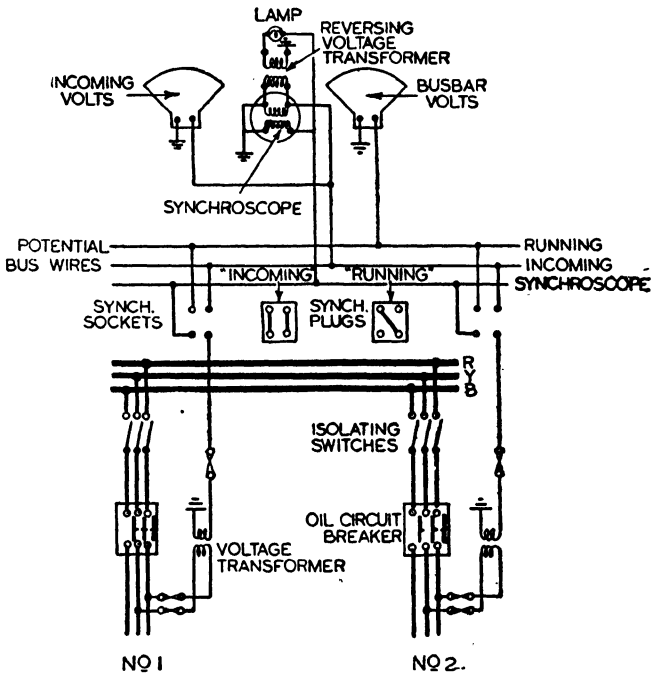


FIG. 7.—CONNECTIONS FOR SYNCHRONISING WITH "LAMP BRIGHT" ON SINGLE BUS BAR HIGH-VOLTAGE SWITCHGEAR.

both the running and incoming windings of the synchroscope. Such transformers are usually connected within the protected zone of the feeder or machine protective gear so that a major fault is limited in its effect to that particular circuit only.

Two synchronising plugs are required with this scheme. The one labelled "running" is inserted in the sockets of a panel controlling a running machine and energises the running bus wire. The one labelled "incoming" is inserted in the sockets of the panel controlling the incoming machine. This latter plug energises the incoming bus wire from the voltage transformer on that panel and at the same time the synchroscope bus wire is made alive from the running bus wire. The synchroscope is permanently connected to the incoming and synchroscope bus wires, as complete isolation is effected by removal of the incoming plug.

The running plug may be left in position in order to obtain indication at all times on the busbar voltmeter.

Where more than two circuits are involved, the voltage transformers must of necessity have similar phases earthed, and a reversing transformer is required in order to obtain lamps bright at synchronism.

Double Busbar Scheme. Machine P.T.'s only.

Fig. 8 is an extension of the previous scheme, but applied to a double busbar system and interlocked to avoid incorrect selection of the running supply.

The running plug should be inserted in the sockets of a panel controlling a supply connected to the same busbars as the incoming supply panel. Should a wrong selection be made, synchronising cannot take

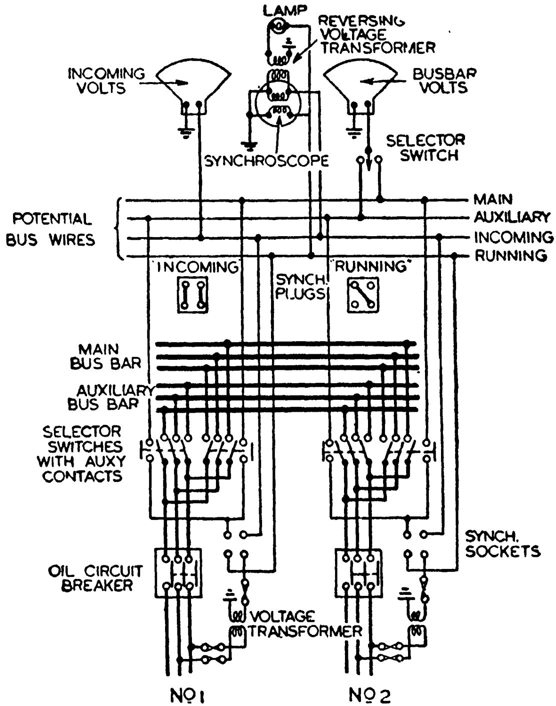


FIG. 8.—CONNECTIONS FOR SYNCHRONISING WITH "LAMPS BRIGHT" ON DUPLICATE BUS BAR HIGH-VOLTAGE SWITCHGEAR.

place, as the potential supply from the running plug is taken through auxiliary switches on the selector switches to the main or auxiliary potential bus wires, according to the position of the selector switches.

The running bus wire can only be made alive from the main or auxiliary potential bus wires through the plug on the incoming panel, and then only if the selector switches on that panel are in the same position

as those on the panel to which the running plug has been applied.

As in the case of Fig. 7, a reversing transformer is required to give the condition of lamps bright at synchronism, and the synchroscope may be completely isolated by removal of the incoming plug.

The running plug may be left in position on any of the running supply panels, and a change-over switch is provided to enable the busbar voltmeter to be connected to either main or auxiliary potential bus wires.

Avoiding Parallel Voltage Transformers.

The foregoing scheme has the advantage that the correct selection of running supply is ensured in a simple manner without introducing the undesirable feature of some schemes whereby the secondaries of voltage transformers are paralleled. This latter arrangement has two serious objections. In the first place reliance must be placed on auxiliary switches to disconnect the secondaries of transformers connected to circuits which have been disconnected from the busbars, and should the auxiliary switches fail to operate correctly, the main conductors of such a circuit, although presumed to be dead, may still be alive through interconnection with other voltage transformers.

The second objection refers to those equipments on which the voltage transformers are employed for important metering purposes. In such cases, in order to obtain the high degree of accuracy demanded, the meters are calibrated to suit the characteristics of the individual transformers to which they are connected. The accuracy of the metering equipment would,

therefore, be impaired if the transformers were deprived of their individuality by connecting their secondaries in parallel.

Automatic Synchronising.

Several forms of automatic synchronising relays are on the market. In one of these the complete equipment is divided into three sections:

(*a*) Speed matching.
(*b*) Voltage equalising.
(*c*) Phase angle equalising.

Each of these operations is carried out automatically, and when the required conditions have been secured the oil circuit-breaker closing circuit is completed

Such a scheme is primarily intended for fully automatic operation of unattended sub-stations, but it may be applied in part to manually controlled stations, in which case the phase angle equalising relay only is utilised as a final check on the operator. The contacts are connected in series with the closing coil circuit to prevent this being completed until the running and incoming supplies are in synchronism.

CHAPTER VI

INSTRUMENT TRANSFORMERS

ALTHOUGH the construction and design of current and voltage transformers differ fundamentally, yet from the user's point of view they are very similar. Each has a primary and secondary winding, the primary for connection in the main circuit and the secondary for connection to the measuring instrument or relay. Each type of transformer has a magnetic core made up of thin pieces of highly permeable iron or one of its alloys.

The primary of a current transformer may consist of a number of turns if the current is low, or of a single conductor passing through the core if the current is fairly high (say 600 amps. or more). If special precautions are taken, single turn or "bushing current transformers," as they are called, can be constructed for currents as low as 50 or 100 amps.

The Rated Burden.

The satisfactory performance of a voltage or current transformer depends largely upon the value of the secondary burden; that is upon the number and impedance of the measuring instruments (and relays) connected to it. Care must therefore be taken that the rated burden shown on the nameplate is not exceeded.

Importance of Instrument Connections.

If an instrument transformer is used to supply a wattmeter, a directional relay, or for some scheme of differential protection, then, in order that the secondary winding of the transformer may with certainty be correctly connected to the apparatus it is to supply, the relative directions of the currents in the two windings of the transformer must be known. Thus, for instance, whilst the indication of an ammeter supplied by a current transformer does not depend upon how the instrument is connected to the secondary terminals, the indication of a wattmeter will reverse if the leads connecting it to the transformer are interchanged.

Again, in a simple Merz-Price protective circuit, the two secondary windings must be joined in series, so that current passes from the secondary winding of one transformer into the secondary winding of the other. The relative directions of the currents in the two windings of an instrument transformer are indicated by giving the pairs of primary and secondary windings similar markings.

Markings of Current Transformers.

Thus, the terminals of a current transformer are marked *M* and *L* on the primary side, and *M* and *L* (circled), as in Fig. 1, on the secondary side. Mere marking of the terminals, however, is not enough; a standard

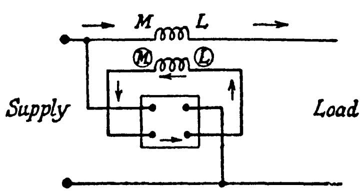


FIG. 1.—ILLUSTRATING THE CONVENTIONAL MARKING OF CURRENT TRANSFORMER TERMINALS.

convention must be fixed to assign a meaning to these markings. The standard British convention is that the instantaneous direction of current in the primary winding of a current transformer from M to L is opposite to the direction of the current in the secondary winding from M to L (circled). This convention is sometimes called subtractive polarity. If the convention is so fixed that the direction of currents in the two windings from similarly marked terminals is the same, this is called additive polarity. This convention is non-standard in this country, but it seems to be used to some extent still in America.

Voltage Transformer Markings.

The standard conventional markings for a voltage transformer are V_1 and V_2 on the primary side, and V_1 and V_2 (circled), as in Fig. 3, on the secondary side. In this case the direction of the currents in the windings from similarly marked terminals is opposite.

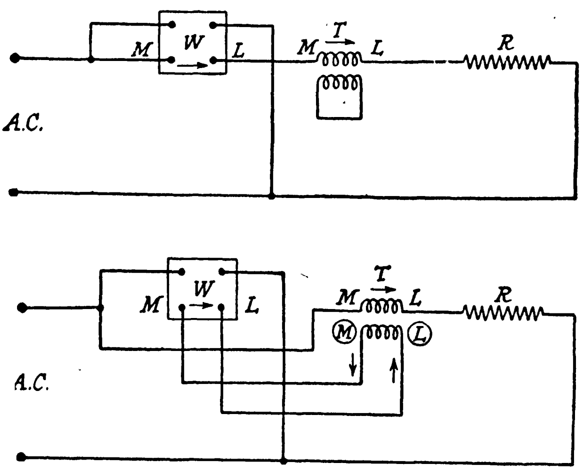
The meaning of the standard convention for current transformer terminal markings will be understood by a brief study of Fig. 1, which shows a current transformer supplying a wattmeter. It is seen from this diagram that opposition of the direction of the currents in the two windings means that the direction of the secondary current in the coil of the wattmeter is the same as if the transformer were disconnected and the connecting leads to similarly marked terminals joined together.

It is easy to see, too, that if the terminals of the wattmeter are marked to show the relative directions of the currents in the two windings for a forward deflection, the instrument can be connected to the current

transformer with the assurance that, when the circuit carries power, the instrument will read correctly, because the two similarly marked terminals of the transformer correspond electrically to the same end of a shunt.

Testing a C.T. for Polarity.

All modern instrument transformers have their terminals marked according to the convention which has been described. Sometimes old transformers, recovered from obsolete gear for use elsewhere, lack these markings. There are many ways of testing an instrument transformer to determine the relative polarities of the two sets of terminals, but few of these methods are applicable to all circumstances. One of



B

FIG. 2.—UNIVERSAL METHOD OF TESTING CURRENT TRANSFORMERS FOR POLARITY.

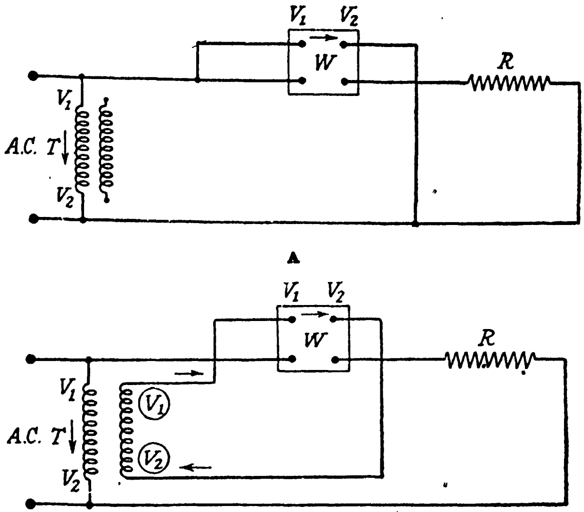
the least known methods of testing is one that is nearly universally applicable, and this method for a current transformer is illustrated in Figs. 2A and B.

A 5-ampere wattmeter *W* is connected in a low-pressure circuit containing the current transformer *T* and a loading resistance adjusted to give about full-scale deflection of the wattmeter. The secondary terminals of *T* are short-circuited, and with the wattmeter deflecting forward its current terminals and the primary terminals of the transformer are marked *M* and *L* in series sequence (Fig. 2A). The wattmeter is then cut out of the main circuit and joined to the secondary of *T* in such a way that, with current passing, it still gives a forward deflection. The secondary terminals of *T* are then marked to correspond to the temporary markings of the wattmeter current terminals (Fig. 2B).

This marking plainly agrees with the standard convention, for the direction of current from *M* to *L* in the primary is the same as the direction of current from *M* to *L* (circled), as in Fig. 2B, in the external circuit of the secondary. The deflection of the wattmeter with the Fig. 2B connections will be only a small fraction of the full-scale value, but even if the ratio of *T* is as high as 1,000/5 this deflection will be one-half per cent of full scale, an amount that is quite sufficient for its correct direction to be detected. Thus, practically any current transformer can be tested in this way by means of a 5-ampere test circuit.

Testing a V.T. for Polarity.

The corresponding method of testing the winding polarities of a voltage transformer is shown in Figs. 3A



A

B

FIG. 3.—STANDARD METHOD OF TESTING VOLTAGI TRANSFORMERS FOR POLARITY.

and B. In Fig. 3A the wattmeter gives full-scale deflection with the current in the loading resistance R, and the voltage transformer T is connected to the supply with its secondary circuit open. The primary terminals T and of the voltage terminals of W are marked V_1 and V_2. The voltage circuit of W is then disconnected from the supply and joined to the secondary terminals of T in such a way that forward deflection is obtained (Fig. 3B).

The secondary terminals of T are then marked to correspond to the temporary markings of the voltage terminals of W. If the ratio of T is 11,000/110, the wattmeter deflection with the Fig. 3B connections will be one per cent. of full-scale value and will be easily

detectable for direction, so that this method of testing is suitable for a wide range of voltage transformers.

Minimum Clearances when Installing Instrument Transformers.

There are several points to observe when installing an instrument transformer. For example, all exposed high-voltage parts of an equipment should have ample clearance from conducting or semi-conducting material. Table IV gives the minimum clearances permissible.

TABLE IV.—MINIMUM CLEARANCES

Line voltage	*Min. distance between live parts of opposite polarity*	*Min. distance between live parts and earth*
660	1·5 inches	1·0 inches
3,000	2·0 ,,	2·0 ,,
6,600	3·5 ,,	2·5 ,,
11,000	5·0 ,,	3·0 ,,
22,000	9·5 ,,	5·5 ,,
33,000	14·0 ,,	8·75 ,,

Earthing the Transformer.

It is essential that the secondary connection and casing of an instrument transformer should be properly earthed. Care must be taken to ensure that the earthing does not interfere with the correct operation of an instrument or relay and it is advisable that the diagram accompanying the transformer should be studied very carefully before the earth connection is made.

Never leave C.T. Secondaries Open Circuited.

An important point to note is that the secondary should never be left open-circuited so long as current

flows in the primary. This magnetises the core to a very high density and may temporarily impair the accuracy; it also causes a dangerously high voltage to be induced acrosss the secondary terminals of a large ratio transformer. If the transformer secondary can be left open-circuited by removing any current carrying device such as a meter, a piece of wire should be used to short-circuit the secondary before any such device is removed.

Do Not Short V.T.

With a voltage transformer, on the other hand, the secondary circuit may be broken with impunity, but must not be short-circuited or it will be burnt out.

Maintenance.

All instrument transformers should be examined regularly, but it must be emphasised that before any inspection is made equipments must be disconnected from the supply; and, to quote the Memorandum of Electricty Regulations, "adequate precautions should be taken to prevent any conductor or apparatus from being accidentally or inadvertently electrically charged when persons are working thereon." In many cases voltage transformers are provided with rollers and it is therefore a simple matter to isolate an equipment by withdrawing it by means of an insulated pole hook, instead of by the provision of separately mounted isolators.

Amongst the chief components to which attention should be given are the insulators, which should be kept clean and undamaged. Oil in oil-immersed transformers should be tested at intervals and if necessary

replaced and brought up to the correct level. All connections and terminals should be examined to ensure that they are secure, and earth connections should be efficiently maintained.

Transformers for Protective Relay Working.

A transformer designed for the operation of meters or instruments is not necessarily suitable for the operation of protective relays. Standard current transformers for metering or instrument purposes having wound primaries will, in most cases, be suitable for relay applications, as will single turn or bar-primary type transformers where the rated current is not less than say, 500 amperes. For bar-primary type current transformers with smaller rated currents, the possibility of inaccuracy is much greater, particularly when the permissible iron core section is limited by considerations of space available in switchgear, e.g., transformers mounted in the bushings of E.H.T. oil circuit-breakers.

The requirements for voltage transformers for protective purposes are not so stringent as for current transformers and any good standard transformer of metering accuracy will be found satisfactory.

CHAPTER VII

PROTECTIVE RELAYS

MODERN methods of power supply, involving the inter-connection of large power stations and their distribution systems, have made possible the liberation of very considerable amounts of electrical energy in the event of a fault. As a result the development of automatic protective systems has become increasingly important, both for safeguarding the generating plant and transmission lines and for maintaining continuity of supply.

OVERCURRENT AND EARTH LEAKAGE RELAYS

One of the earliest and simplest means of protecting almost all classses of electrical apparatus was the provision of overcurrent and earth leakage protection, and although in recent years many specialised schemes have been evolved for dealing with various types of apparatus, the overcurrent and earth leakage principle remains the most universally applied. Its popularity is due chiefly to its simplicity, reliability, and comparative economy. The types of overcurrent and earth leakage gear employed, range from the direct-acting coils used in small switchgear to the modern current-transformer-energised relays operating in conjunction with the larger circuit-breakers.

Basic Principles of Overcurrent and Earth Leakage Protection.

The basic principles of overcurrent and earth leakage are nowadays a matter of common knowledge. Fig. 1 gives an example of a simple overcurrent group consisting of three current transformers and a three-element relay. Excess current in any phase is reproduced in

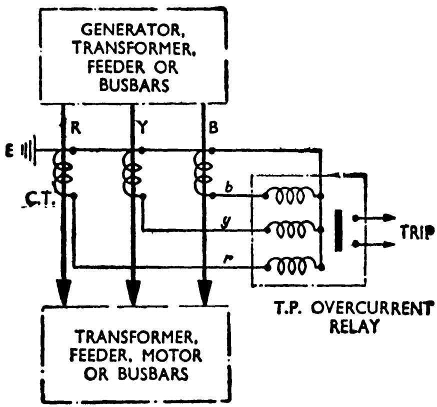


FIG. 1.—OVERCURRENT PROTECTION FOR THREE-PHASE THREE-WIRE OR THREE-PHASE FOUR-WIRE.
(*G.E.C.*)

the secondary of the current transformer and hence in the relay. At a predetermined current value the relay operates so as to close its contacts, thereby tripping the associated circuit-breaker.

A simple earth leakage scheme is illustrated on Fig. 2. Under all conditions, normal and abnormal, no current will flow in the relay so long as the sum of the phase currents is zero. However, should an earth leakage develop, the sum will no longer be zero and an

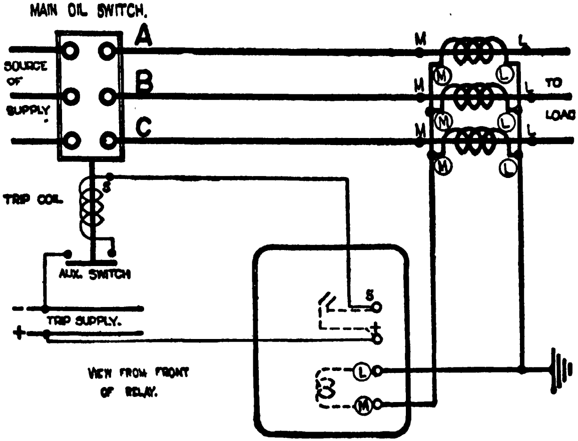


FIG. 2.—EARTH LEAKAGE PROTECTION FOR THREE-PHASE THREE-WIRE.

The three current transformers are shown connected in parallel across the terminals of the current coil of the single pole earth leakage relay.

When the relay closes the two contacts between the two connections labelled S and + the trip coil circuit is closed, its solenoid is energised and the main switch is opened.

(*Nalder Bros. & Thompson, Ltd.*)

out-of-balance current will appear in the relay coil, causing it to operate.

Inductive Type Relay.

The relay now in most common use is the induction type, with inverse and definite minimum time characteristic (Fig. 3). The operating element takes the form of an eddy current induction-disc motor; this is arranged to operate in a time that varies inversely as the operating current, down to a limiting value, when the delay becomes sensibly constant regardless of further increase of current. It will be seen that the discriminating

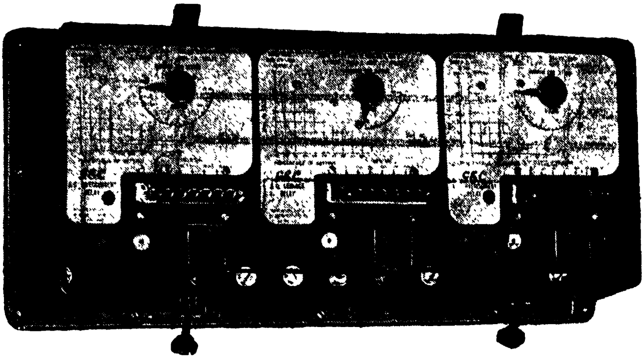


FIG. 3.—G.E.C. TRIPLE POLE RELAY GIVING FULL OVERCURRENT AND EARTH LEAKAGE PROTECTION FOR THREE-PHASE THREE-WIRE.

Showing case containing two overcurrent elements and an earth leakage element in the centre.

(*G.E.C.*)

feature of the relay is embodied in the induction-disc motor, the timing of which can be varied by altering the distance through which the disc rotates. The current setting is made in connection with the operating coil which is tapped and connected to a plug-setting board which gives a 4:1 current range in seven tappings.

With this system of protection, therefore, the breakers controlling various sub-circuits can be so timed as to open in predetermined sequence in the event of a fault. In this way general interruption of the supply, on account of minor faults or local overloads, is avoided.

Fig. 4 shows graphically the timing characteristics of the relay. Curve A indicates the characteristics of a 2 sec. d.m.t. (definite minimum time) setting, while curves B, C, and D represent settings of 1.5, 1.0, and 0.5 sec. d.m.t. respectively.

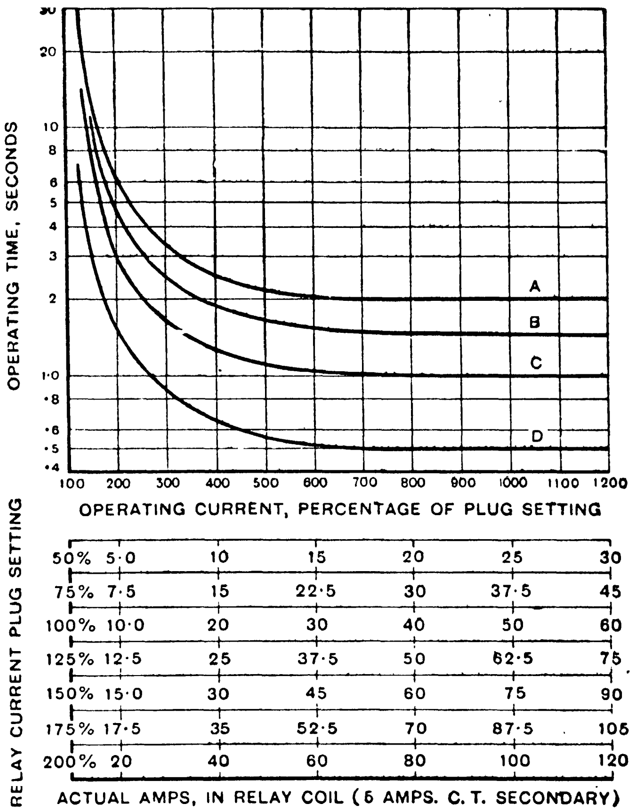


FIG. 4.—TIMING CHARACTERISTICS OF A G.E.C. THREE-POLE OVERCURRENT RELAY.

Comparing, for example, curves A and C, it will be seen that, for any value of current, the time ordinate of C is always half that of A; any other time setting will give an operating time in proportion. The current scale is graduated in percentage of plug setting, so that, for a 200/5 amp. current transformer operating with a

relay on the 125 per cent. plug setting the primary current corresponding to the 400 per cent. ordinate is $\frac{400}{100} \times \frac{125}{100} \times 200$ amps. $=1{,}000$ amps., and the corresponding time of operation is 2.5 sec. at the 2-sec. d.m.t. setting, 1.25 sec. at the 1-sec. d.m.t. setting, and so on for other settings.

The table at the bottom of Fig. 4 shows, for various settings, the actual currents in a relay coil fed from a current transformer designed to give a secondary current of 5 amps. at full load.

The curves A, B, C, and D may be regarded as the settings of four different relays protecting four different pieces of apparatus on the same supply system. For overloads in excess of approximately 650 per cent. of full load current—as for example a short circuit—the curves all run parallel to the base, and the relays will operate in definite sequence in 0.5, 1.0, 1.6, and 2 seconds respectively. Positive time discrimination is thus secured, so that the circuit-breaker nearest to the fault will open before any of the others is affected.

Protective Current Transformers.

Considerable importance attaches to the correct design of current transformers used in connection with overcurrent and earth leakage relays, particularly with the latter. Most standard 15-VA Class C transformers are suitable, but where bushing or through type transformers having only one primary conductor are used for currents less than 1,000 amps., care must be taken to ensure sufficient secondary overload capacity to bring the overcurrent relay to its definite minimum time. When such current transformers have to operate

in conjunction with an earth leakage relay, it is very desirable that they should be accurately balanced and have no other secondary burden to upset this balance.

The earth leakage arrangement shown in Fig. 2 ensures maximum sensitivity and stability. Similar precautions are necessary when low ratio wound type current transformers, designed for maximum fault currents exceeding approximately 15 times their normal rating, are used.

Applications of Discriminative Overcurrent and Earth Leakage Protection.

The main applications of the relays described above are the protection of (*a*) generators; (*b*) busbars; (*c*) transformers; (*d*) feeders, both overhead and underground; and (*e*) motors.

The arrangement in Fig. 1 is applicable to all the five types of apparatus listed. The relay must be set to operate at a current in excess of the normal full load of the apparatus protected, and the timing adjusted with relation to that of associated gear. Instruments can be connected in series with the relay, when average current transformers are used, without detriment to the protection.

The 3-wire earth leakage arrangement shown in Fig. 2 illustrates an effective means of rapidly isolating an internal earth fault within a power transformer. A d.m.t. setting of the order of 0.2 to 0.5 sec. ensures stability against current transformer errors due to switching surges and heavy through fault currents. A relay current of 10 per cent. can generally be used with complete stability. This class of protection can also

be employed for earth fault protection on feeders, and is generally adopted on industrial gear, such as the sensitive earth leakage protection of cables in mines, where settings as low as 5 per cent. of normal full load can be obtained.

This arrangement can also be applied to the protection of motors, but the method shown in Fig. 5 is usually employed. As an alternative to the three-line current transformers a single core-balance current transformer embracing all three phases can be used

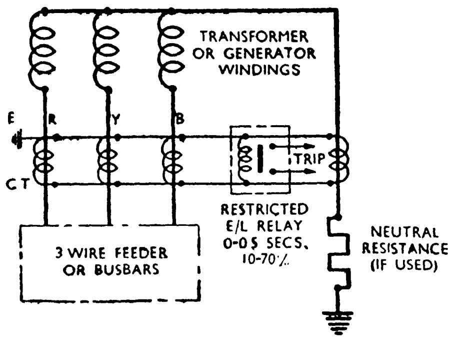


FIG. 5.—RESTRICTED EARTH LEAKAGE PROTECTION FOR THREE-PHASE THREE-WIRE. (*G.E.C.*)

as shown in Fig. 23. With either arrangement the results obtained are identical.

The arrangement given in Fig. 6 is probably the most popular form of overcurrent and earth leakage protection. It affords full protection with only three current transformers and a minimum of three relay elements, which can be housed in one triple-pole case, and is used successfully for the protection of transformers, feeders, and motors. Given average current transformers, protection equivalent to that provided by

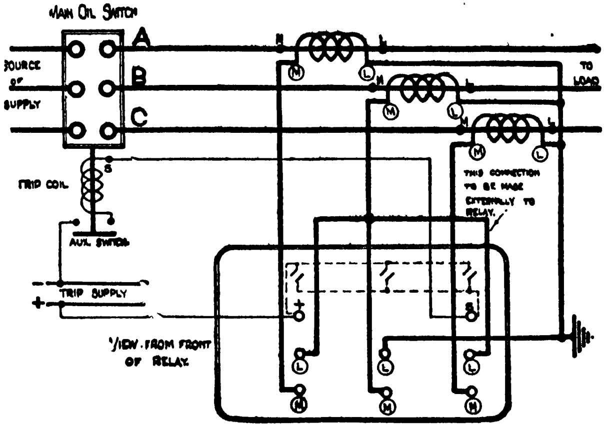


FIG. 6.—COMBINED OVERCURRENT AND EARTH LEAKAGE PROTECTION FOR THREE-PHASE THREE-WIRE OR TWO-PHASE THREE-WIRE.

Showing a triple-pole relay—with one earth leakage element between two overcurrent elements.

(Nalder Bros. & Thompson, Ltd.)

the arrangements shown in Figs. 1 and 2 combined can in many cases be obtained.

Fig. 5 illustrates one of the best forms of earth fault protection for a transformer or generator winding, when either star-connected with earthed neutral or when delta-connected and using an inter-star earthing transformer. Protection is restricted to the windings and the connections thereto, and only in the event of an earth fault in this zone will the earth leakage relay operate. Faults outside the protected zone, regardless of the location of the power sources, do not affect the relay. In the interests of stability it is generally advisable to use the four associated current transformers for no other purpose than the earth leakage protection. With average current transformers a relay

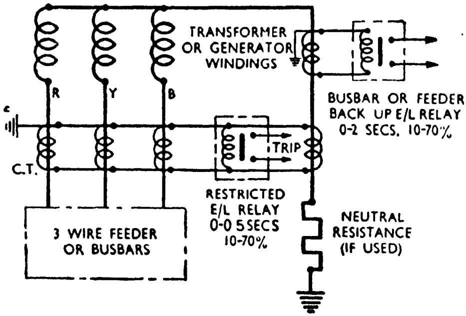


FIG. 7.—RESTRICTED EARTH LEAKAGE PROTECTION FOR THREE-PHASE THREE-WIRE WITH BACK-UP PROTECTION.
(*G.E.C.*)

setting of 10 per cent. can be used and a d.m.t. of 0.2 sec. is recommended.

The principle of operation of the arrangement in Fig. 8 is the same as that in Fig. 5, but a fourth wire is shown, as in the case of a L.T. distribution system. Here also the earth leakage relays operate only in the event of an internal fault and are immune from all other conditions of unbalance. Settings similar to those shown in Fig. 5 are recommended.

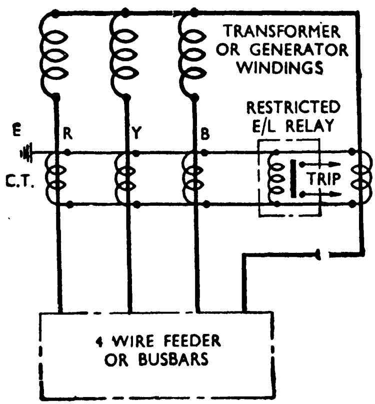


FIG. 8.—RESTRICTED EARTH LEAKAGE PROTECTION FOR THREE-PHASE FOUR-WIRE.
(*G.E.C.*)

Back-up earth leakage protection

can be applied to perform one or several of a variety of functions. As applied in both Figs. 7 and 9, it provides a back-up to the restricted earth leakage group. The setting must not be below that of the connected apparatus. A setting from 1 to 2 sec. is usual. As applied to Fig. 9 when a neutral earthing resistance is used the relay can be set with relation to the thermal rating of the resistance.

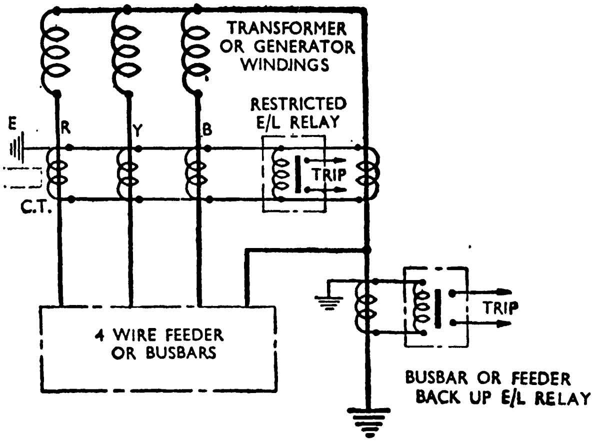


FIG. 9.—RESTRICTED EARTH LEAKAGE PROTECTION FOR THREE-PHASE FOUR-WIRE WITH BACK-UP PROTECTION.
(*G.E.C.*)

Protection of a Complete System.

Discriminative overcurrent and earth leakage protection of a complete system, including generator, busbars, transformers, feeders and motors is shown in the diagram in Fig. 10. All five types of equipment are interconnected in a manner typical of modern practice. The various forms of protection shown in

Figs. 1, 2, 5, 6, 7, 8, and 9 are indicated by the numbers in brackets preceding the time settings, and suitable

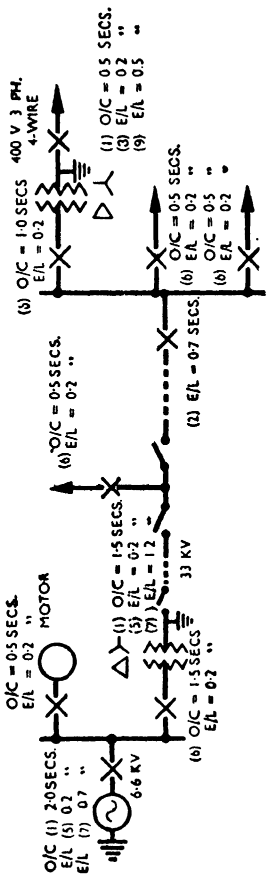


FIG. 10.—SCHEME OF DISCRIMINATIVE OVERCURRENT AND EARTH LEAKAGE PROTECTION FOR GENERATORS, BUSBARS, TRANSFORMERS AND FEEDERS (FOR DETAILS OF PROTECTION SEE TABLE V).

NOTE.—The numbers in brackets preceding the time settings correspond to the figure numbers of the appropriate diagrams of connections of the individual protection afforded at each particular section of this general diagram.

(G.E.C.)

timings are given. Such a system is fully protected, and a minimun of gear isolated in the event of a fault.

Considering the scheme in detail, the protection

afforded, starting from the power source is set out in Table V.

TABLE V.—GIVING DETAILS OF PROTECTION AFFORDED.

Apparatus.	*Protective Group.*	*Extent of Protection.*
	Fig.	
Generator	1	Excess of current.
	5	Internal earth faults.
6.6-kV. busbars (current transformer in generator neutral, ...	7	Earth faults.
6.6-kV. motor	6	Excess current. Internal earth faults.
6.6/33-kV. transformers.	6	L.V. phase faults. L.V. earth faults.
	5	H.V. earth faults.
	1	L.V. and H.V. excess currents.
33-kV. transmission line	1	Excess currents.
	7	Earth faults.
Tee off	6	Excess current. Earth fault.
33-kV. busbars	2	Earth faults.
33-kV./400-V. transformers	6	H.V. & L.V. phase faults. H.V. earth faults.
	8	L.V. earth faults.
	1	H.V. or L.V. excess currents.
400-V. distribution ..	1	Excess current.
	9	Earth fault.
33-kV. feeders	6	Excess current, phase or earth faults.

Protective Relays for Duplicate Feeders.

With duplicate feeders, as in a simple radial feeder, the normal direction of power flow is from the source outwards. In such feeders, however, as will be seen from Fig. 11*a*, a fault may be fed from both ends of the

faulty feeder; that is, a fault at E will be fed direct from A, and also via the feeder BD, from C. This feed back will, of course, only occur if the fault is of such a magnitude as to reduce the voltage at E to a value below that at D. This reversal of the normal power flow is an additional result of abnormal conditions, and full protection demands the provision of automatic

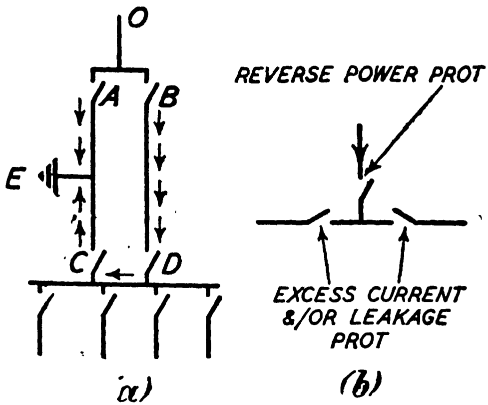


FIG. 11.—ILLUSTRATING VARIOUS METHODS OF PROTECTING FEEDERS AGAINST THE HEAVY CURRENT FLOWING ON THE OCCURRENCE OF A FAULT.

(*a*) Duplicate feeders. (*b*) Ring main arrangement.

switches at both ends of feeders running in parallel. Usually some form of reverse power relay is provided at the remote ends of the feeders, and excess current and/or leakage protection at the ends nearest the source.

Ring Main Arrangement.

In the case of a ring main arrangement, the feeders to the ring operate in exactly the same conditions as do feeders in parallel, and require the same protection.

The power flow in any section of the ring itself may vary in direction, depending on the number and position of the feeders working. Obviously, the cables in the ring need some protection, otherwise a fault here will cause a total shut-down of all the feeders before it is cleared. This protection usually takes the form of excess current and/or leakage protection, and is provided at all points where the ring is fed, as is shown in Fig. 11*b*.

Use of Reverse Power Relays.

The protection given by reverse power relays is perhaps not ideal, but it involves the least complication in both control gear and cables, and it is doubtful if further complication would be introduced into industrial systems to overcome its shortcomings. Much depends upon the type of relay used, for some designs are much too sensitive to voltage fluctuations to be entirely satisfactory. Probably the most reliable type is that based on the wattmeter, with suitable modifications to allow for voltage fluctuations, and the distortion of the voltage triangle in fault conditions. Relays of this type operate satisfactorily on voltages as low as ten per cent. normal.

There are, of course, circumstances in which a reversal of power can take place while a feeder is sound. For instance synchronous machinery will feed back momentarily if the voltage at the source is affected by a fault elsewhere on the system. This tends to upset the accuracy of the reverse power protection unless some restraint is placed on the action of the relays.

Normally the reverse power relays should be adjusted

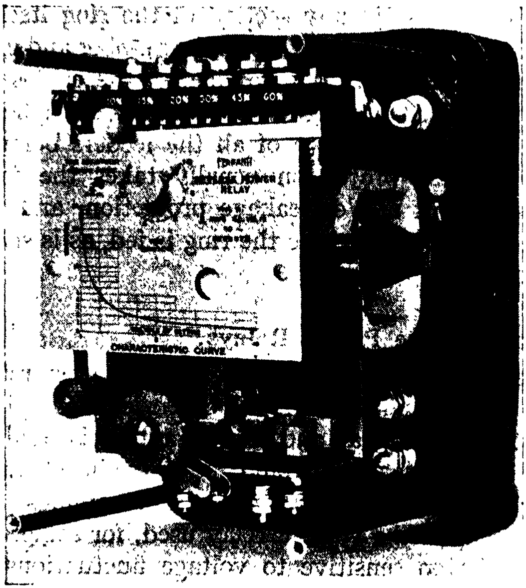


FIG. 12.—REVERSE POWER RELAY.

so as to trip before the protective devices at the source of supply, thus leaving the breakers at this end finally to clear the fault. This means that some form of definite time limit relay should be used on the over-current protection at this end of the feeders.

Usually a reverse power relay is provided in each phase, but if reverse power protection to prevent an alternator motoring is required, then a relay in one phase only is all that is necessary.

This form of protection is equally well applied to any other form of paralleled supplies, such, as for instance, transformers which are paralleled on the secondary side.

Differential Systems of Protection.

Mention should be made of differential systems of protection, operating on differences of currents which under normal working conditions are equal in magnitude.

Fig. 13 shows an elementary single-phase differential protection circuit, where *CT* is a current transformer, *M* is a motor, transformer, or other plant item, and *R* is the protective relay.

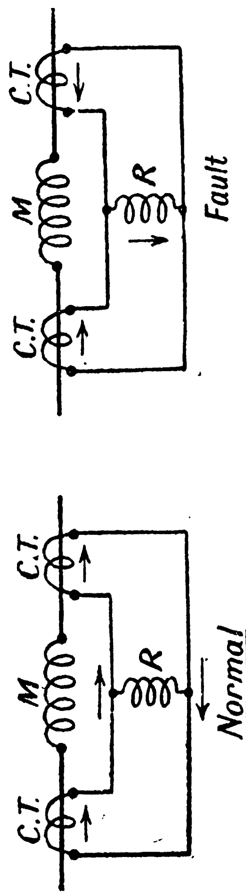


FIG. 13.—SINGLE-PHASE DIFFERENTIAL PROTECTION CIRCUIT UNDER NORMAL AND FAULT CONDITIONS.

Just so long as there is no fault in the system, current will flow equally in both transformer secondary windings, and will circulate in the series circuit but will not flow through the shunt relay coil. When a fault occurs in the transformer primary circuits, one of the transformers will carry a current in excess of the other and this difference will be repeated in the secondary windings, causing the difference of the transformer currents to flow in the relay winding.

Construction of Earth-leakage and Overcurrent Relays.

Earth-leakage relays are

similar in construction to those normally used as overload relays, and their various methods of operation depend more upon external connections than on any changes made in the relay itself.

A single-pole earth-leakage relay is illustrated in Fig. 14. The construction of one of these relays is

FIG. 14.—SINGLE-POLE EARTH-LEAKAGE RELAY.

This shows the time-setting dial, the current-setting plug, and a portion of the characteristic curve. The knob marked "reset" is to restore the moving contact to its normal position after the relay has operated.

(*A. Reyrolle & Co., Ltd.*)

illustrated more clearly by Fig. 15, from which it will be seen that it consists of three essential parts, an electro-magnet, an aluminium induction disc, and a gravity-controlled quadrant carrying the moving contacts. It operates on the shaded-pole motor principle, the motive power being obtained from interaction between the shaded poles of the electro-magnet and the aluminium disc, which is arranged to rotate between the pole-pieces. The shading consists of copper rings surrounding half the pole faces; and the magnetic flux reaches its maximum value in the shaded half of the pole face later than in the unshaded half. Eddy currents in the disc due to these fluxes interact with one another and tend to drag the disc away from the unshaded part of the pole face and between the shaded portion. Thus a torque is produced on the disc.

Operation.

On the same shaft on which the disc is mounted there is a pinion, carrying with the gravity-controlled quadrant a moving contact; rotation of the disc winds up that quadrant until the moving contact connects with the fixed contact, and completes a circuit which will trip the breakers. The speed of rotation of the disc, and therefore of the lifting of the quadrant, will be proportional to the magnitude of the current.

Characteristics of Protective Relays.

On a modern relay it is possible to carry out an adjustment of the rate at which the relay will operate. This characteristic, styled the time-current constant of the relay, is controlled by means of a permanent magnet, shown at the top of Fig. 15, so arranged that

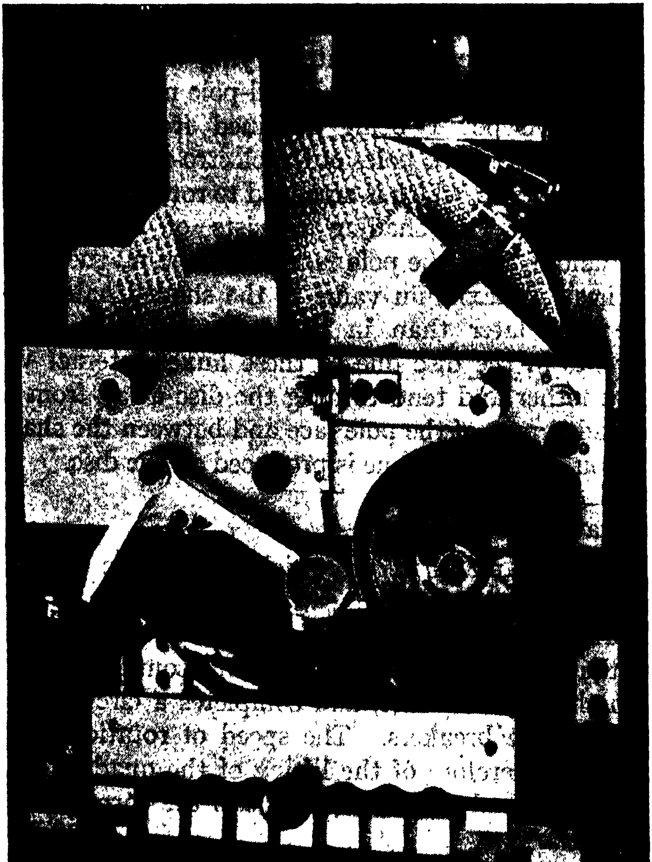


FIG. 15.—RELAY MOVEMENT REMOVED FROM ITS CASING.

The fixed and moving contacts are shown in the operating position. Normally, the quadrant would be concealed within the frame and the two contacts nearly 1 in. apart.

(A. Reyrolle & Co., Ltd.)

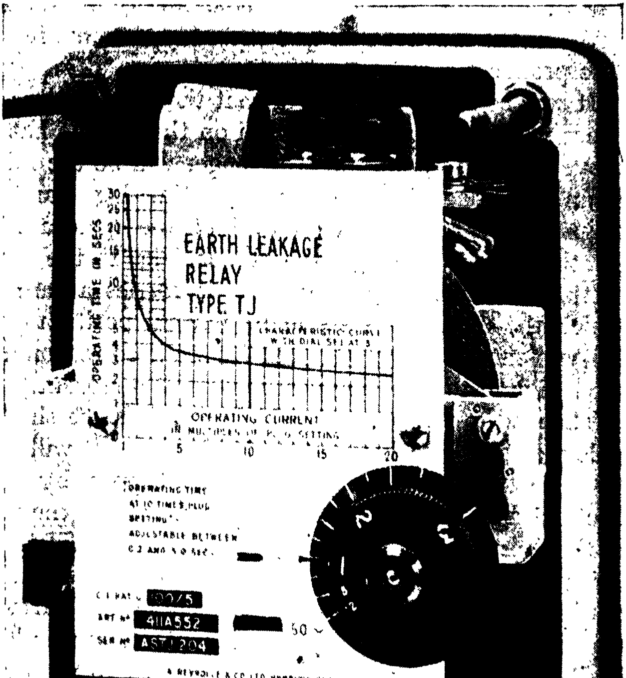


FIG. 16.—EARTH-LEAKAGE RELAY WITH FRONT COVER REMOVED.

The characteristic curve appears on the chart correct for a time-setting of three seconds.

(*A. Reyrolle & Co., Ltd.*)

the disc moves between its pole faces; interaction between the magnet flux and the eddy currents in the disc produces a breaking effect.

It will be seen from Fig. 15 that the greater the distance which the small gearwheel on the spindle has to move along the quadrant, the longer will be the minimum time-lag. This minimum time-lag can be adjusted by altering the travel of the quadrant in relation to the small gearwheel. In Fig. 16 the time-setting dial can be clearly seen; it carries a cam on which the quadrant rests in its normal position, and hence a movement of the dial causes a corresponding alteration in the starting position of the quadrant.

The electro-magnet coil, which energises the shaded pole-pieces, is clearly visible in Fig. 15; and it will also be seen that this energising coil is tapped by connections brought out to a row of contacts at the foot of the illustration. By means of a current-setting plug it is possible to arrange that the value of the operating current can be altered without opening the current-transformer circuit. This row of contacts is provided with a scale varying from 10 per cent. to 70 per cent. of the rated current of the transformer; and even if the plug is inadvertently left out the relay automatically picks up an earth-leakage setting of 40 per cent. of normal current, so that this error does not nullify its protective uses.

Another Type of Relay.

Internal connections of another type of earth-leakage relay are shown in Fig. 17. The principle of operation of this non-directional relay, intended to be used where the direction of fault-current flow need not

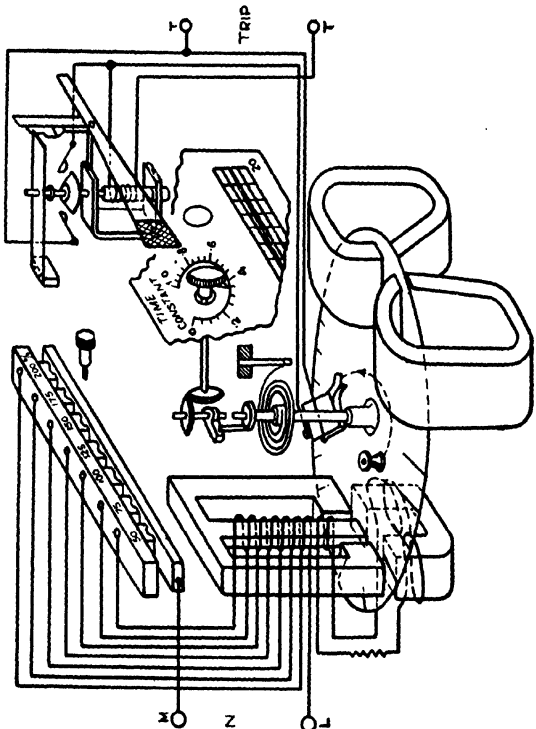


FIG. 17.—INTERNAL ARRANGEMENT OF FERRANTI RELAY.

The two large permanent magnets at the foot are for damping purposes. The contacts which close the trip circuit are shown at the right-hand corner.

(Ferranti, Ltd.)

enter into consideration, is similar to that of an induction-type watt-hour meter. The disc is driven by the two electro-magnets at the left of Fig. 17; one winding on the top electro-magnet is fed from the current transformer with which the relay is used, and the other on the same magnet acts as a secondary winding, to energise by transformer action the electro-magnet core placed below the disc.

These two fluxes displaced in phase result in a driving force which causes rotation. Damping is once again

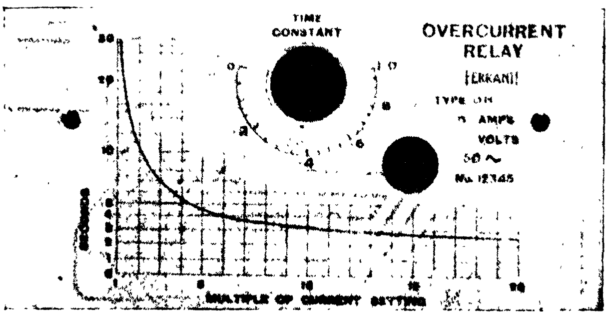


FIG. 18.—TIME/CURRENT CURVE FOR FERRANTI RELAY.

provided by the two permanent magnets, and control is affected by means of a spring. Compensation for the increasing torque of the spring as the disc is rotated is obtained by slots cut in the disc to varying depths, which interrupt the eddy currents at those points.

Under normal conditions the spring holds the disc against a back stop, but when an overload or earth fault comes on the disc moves forward, carrying a small contact shaped like a capstan which finally bridges two contacts after travelling along the dotted

line marked on the surface of the disc and indicated by an arrow in Fig. 17. The position of the back stop and hence the operating time is adjusted through a system of bevel gears.

The diagram also shows the connections from the main winding to the tapping board, and the means by which the plug conveys the current from the selected tapping to the outside terminal M of the instrument.

Time settings are regulated by means of the knob marked "Time Constant." This is shown diagrammatically together with a portion of the dial of the instrument in Fig. 17, but the characteristic curve and the time-constant knob also appear in Fig. 18. The pointer on this knob travels over a quadrant graduated from 0 to 1.0, representing the constant by which the time taken from the curve should be multiplied to give the actual operating time applying to the particular current setting in use. On standard relays the definite minimum time is 2 sec.; this could be increased in special cases up to 4 sec. with an increase in the wattage. The consumption of the standard form of relay does not exceed 2.0 V.A. at the operating value.

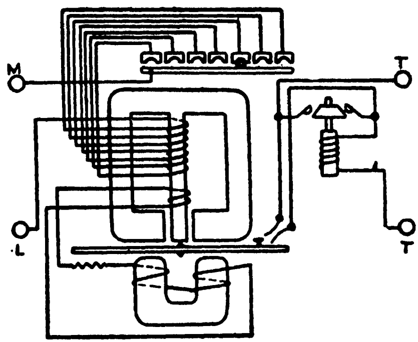


FIG. 19.—INTERNAL CONNECTIONS OF NON-DIRECTIONAL RELAY.
(*Ferranti, Ltd.*)

As in relays shown previously, the contacts are self-

aligning and will deal with 350 V.A. with a maximum of 3 amps. Above these values it is usual to connect in parallel auxiliary contacts, operated electrically, of a type which would deal with 20 amps. and 660 volts, A.C. or D.C.

Fig. 19 shows internal connections of a non-directional relay.

Directional Relays.

The general principles of directional protective relays are almost exactly the same as those just described; directional relays are inoperative when fault current flows in the predetermined direction, but on reversal they operate with a characteristic similar to that of the non-directional relays dealt with under the previous heading. It is necessary, therefore, to provide facilities for discrimination, in addition to the overload protection with a time-element.

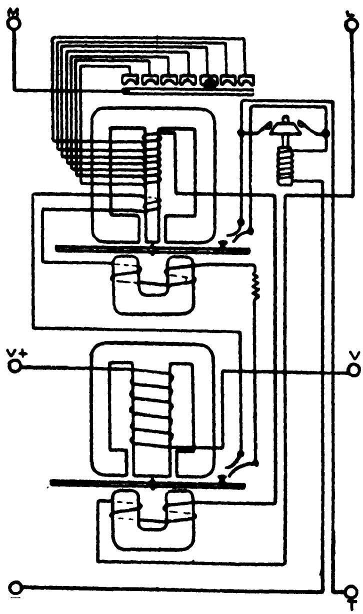


FIG. 20.—INTERNAL CONNECTIONS OF DIRECTIONAL RELAY.
(*Ferranti, Ltd.*)

Referring again to Fig. 17, the general construction of the directional type of relay requires only the

addition of the directional element; it will be on the same principle as a wattmeter, with current and voltage coils operating on a disc, driving it in a direction depending upon the flow of power. The circuit from the secondary winding on the top core of the magnet shown in Fig. 17 would be taken through a pair of contacts on the directional element, and these are shown in Fig. 20, at the righthand end of the wattmeter type

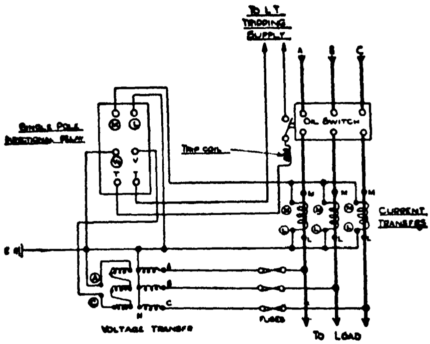


FIG. 21.—DIRECTIONAL EARTH-LEAKAGE PROTECTION, USING DELTA SECONDARY OF VOLTAGE TRANSFORMER.

This shows a single-pole relay on a three-phase, three-wire system.

(*Ferranti, Ltd.*)

of disc between the poles of the lower pair of electromagnets.

Under directional earth-leakage conditions the voltage coil of this relay is energised only under fault conditions. The usual method is to connect the voltage coil in series with the delta secondary of a voltage transformer, or alternatively to wind the directional element coil for current operation, and connect it to a current transformer in the earthed

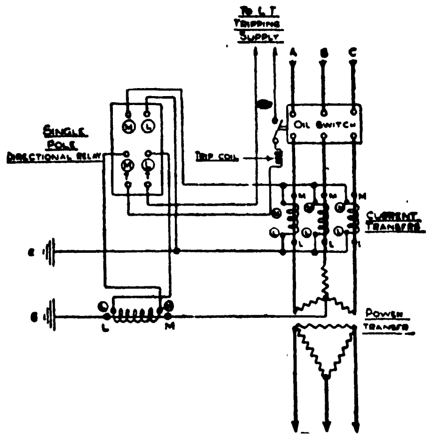


FIG. 22.—DIRECTIONAL EARTH-LEAKAGE PROTECTION, USING CURRENT TRANSFORMER IN POWER TRANSFORMER NEUTRAL.

This shows a single-pole relay on three-phase three-wire circuit.

(*Ferranti, Ltd.*)

neutral connection of the supply. The connections in both these cases are shown in Figs. 21 and 22.

Core-balance Leakage Protection.

The fundamental principle of the core-balance system is that if there is no leakage the algebraic sum of the current flowing at any moment in the three conductors of a three-phase system is zero. Under these conditions there will be no magnetism induced in the common iron core of the core-balance current transformer shown in Fig. 23. Directly sufficient leakage occurs, this balance is disturbed, and there is an excess of current in one phase over the other two, or in two phases over the other one; the core becomes magnetised, and induces a current in the secondary

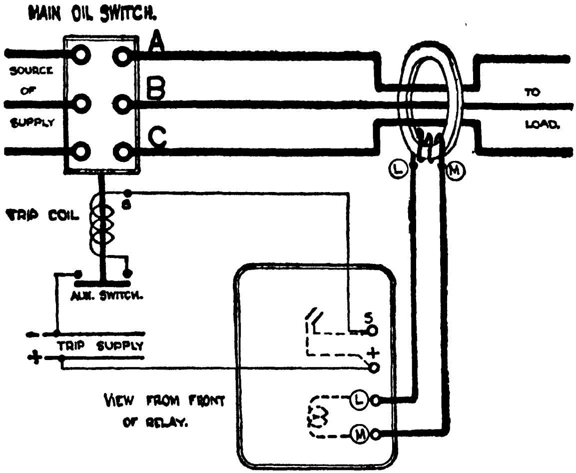


FIG. 23.—CONNECTIONS FOR CORE-BALANCE PROTECTION.
(*Nalder Bros. & Thompson, Ltd.*)

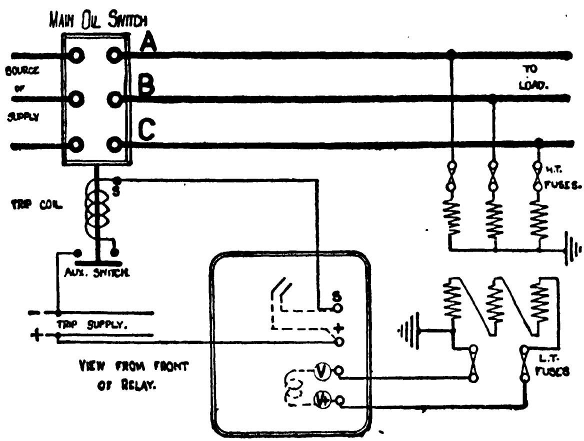


FIG. 24.—CONNECTIONS FOR RESIDUAL-VOLTAGE RELAY.
(*Nalder Bros. & Thompson, Ltd.*)

winding (*LM*, *LM* of Fig. 24); this in turn energises the relay winding as previously described.

Voltage-operated Relays.

A voltage-operated relay, energised from the secondary windings of a star/open-delta voltage transformer, is shown in Fig. 24. So long as equal voltages exist between each phase and earth, no voltage will appear between the two points in the delta winding where the relay is connected; when one phase is earth-faulted, the voltage across the points V and $V+$ will operate the relay.

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